THE RELATIONSHIP BETWEEN STEM-FORM, STAND-CLOSURE AND SITE-CONDITIONS:

the influence of environmental conditions
on tree allometry and forest structure
in west-central Alberta

by

Kathleen E. Jaques, B.Sc., B.Sc.(Agr)

A Thesis
submitted to the Department of Biological Sciences
in partial fulfillment of the requirements
for the degree of
Master of Science

November 1995
Brock University
St. Catharines, Ontario

ABSTRACT

Changes in the configuration of a tree stem result in significant differences in its total volume and in the proportion of that volume that is merchantable timber. Tree allometry, as represented by **stem-form**, is the result of the vertical force of gravity and the horizontal force of wind. The effect of wind force is demonstrated in the relationship between **stem-form**, **stand-closure** and **site-conditions**. An increase in wind force on the individual tree due to a decrease in stand density should produce a more tapered tree. The density of the stand is determined by the conditions that the trees are growing under. The ability of the tree to respond to increased wind force may also be a function of these conditions. This **stem-form/stand-closure/site-conditions** relationship was examined using a pre-existing database from west-central Alberta. This database consisted of environmental, vegetation, soils and timber data covering a wide range of sites. There were 653 sample trees with 82 variables that formed the basis of the analysis. There were eight tree species consisting of *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa*, *Larix laricina*, *Populus tremuloides*, *Betula papyrifera* and *Populus balsamifera* plus a comprehensive all-species data set.

As the actual conformation of the stem is very individual, **stem-form** was represented by the diameter at breast height to total height ratio. The four **stand-closure** variables, **crown closure**, **total basal area**, **total volume** and **total number of stems** were reduced to **total basal area** and **total number of stems** utilizing a bivariate correlation matrix by species. **Site-conditions** were sub-divided into macro, meso and micro variables and reduced in number

using cross-tabulations, bivariate correlation and principal components analysis as screening tools. The **stem-form/stand-closure** relationship was examined using bivariate correlation coefficients for **stem-form** with **total number of stems** and **stem-form** with **total basal area**. The **stem-form/site-conditions** and the **stand-closure/-site-conditions** relationships were examined using multiple correlation coefficients. The **stem-form/stand-closure/site-conditions** relationship was examined using multiple correlation coefficients in separate analyses for both **total number of stems** and **total basal area.**

An increase in **stand-closure** produced a decrease in **stem-form** for both **total number of stems** and **total basal area** for most species. There was a significant relationship between **stem-form** and **site-conditions** and between **stand-closure** and **site-conditions** for both **total number of stems** and **total basal area** for most species. There was a significant relationship between the **stem-form** and **site-conditions**, including the **stand-closure**, for most species; **total number of stems** was involved independently of the **site-conditions** in the prediction of **stem-form** and **total basal area** was not. *Larix laricina* and *Betula papyrifera* were the exceptions to the trends observed with most species.

The influence of both **stand-closure** (**total number of stems** in particular) and **site-conditions** (**elevation** in particular) suggest that forest management practices should include these ecological parameters in determining appropriate restocking levels.

ACKNOWLEDGEMENTS

I would like to especially thank my supervisor, Dr. J. Middleton, for his interest and support through what has become a lengthy process in producing this thesis. His comments and suggestions during the past six years have been invaluable. I would also like to thank Dr. M. Dickman and Dr. R. Morris, who have both served as my thesis committee chairman, as well as Dr. D. Ursino and Dr. R. Kerman for their comments during the reviews of my progress.

I would like to extend my appreciation to the members of Alberta Environmental Protection who assisted in the procurement of the database. In particular, I would like to thank Elaine Anderson for all of the arrangements for mailing tapes, photographs and plot information whenever I required it. Her thoroughness and prompt response have made it possible for me to complete this analysis. I would also thank Norbert Kondla, Ken Dutchak and Basil Delaney for providing permission to utilize these data. I would also like to thank Stan Nichols of Fletcher Challenge for permission to use British Columbia Forest Products data.

The analysis of these data was a long and complicated process and it was greatly facilitated by the many members of Brock University's Computing and Information Services. I would like to thank Clyde Fenn, Mitzi Banders, Andrew Morgan, Brad Saxton and Michael Grau for patiently providing me with excessive amounts of memory and assistance with tapes, remote connections and SPSSx.

I would like to express my appreciation to my friends and family. I would like to thank my former husband, Bruce Bennett, for his support and my long-suffering children, Ryan and Lorna, for

their patience during the many hours that were spent on this thesis. I would like to convey my thanks to my parents, John and Harriet Jaques, and my friends, Liliana Haynes, Laurie Iker, Kathy Brown and Nancy Piluso for reliable child-care and moral support. Lastly, I would like to remember a dear friend, the late Elizabeth Baker Rigbey, who believed that education is a life-long process.

TABLE OF CONTENTS

Chapter Page

Chapter Page

LIST OF FIGURES

LIST OF TABLES

LIST OF PHOTOGRAPHS

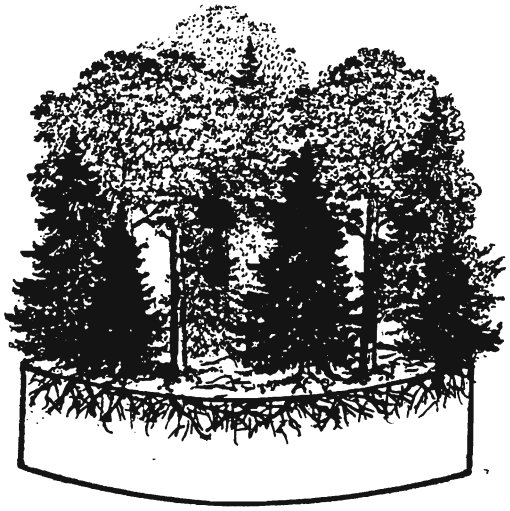
1. INTRODUCTION

The purpose of this thesis is to examine the relationship between **stem-form** (a component of tree allometry), **stand-closure** (the density of the surrounding forest) and the **site-conditions** under which the tree is growing. The influences on tree growth can be discussed as **site-conditions** at the macro, meso and micro level; **stand-closure** itself is reflected as a meso influence on an individual tree (Figure 1). Macro influences affect both meso and micro site conditions. Meso and micro influences cumulatively affect the macro level of **site-conditions.**

This study utilizes an extensive, pre-existing database of environmental, vegetation, forestry and soils data originating in the foothills of Alberta to test the hypothesis on this relationship. This relationship will be referred to hereafter as the **stem-form/stand-closure/site conditions** relationship; the component relationships will be referred to as the **stem-form/stand-closure** relationship, the **stem-form/site-conditions** relationship and the **stand-closure/site-conditions** relationship.

The form that a tree assumes is considered to be the result of the external forces of wind and gravity. In order to maintain an upright stance and effectively compete for light, these forces must be counter-balanced by adjustments in the taper of the tree stem. The intensity of competition for light is determined by the density of the stand surrounding the individual tree. The density of the stand is determined by an array of environmental conditions. At the macro level, climate and topography impose restrictions on stand growth; at the meso level, the size and form of nearest

Macro Scale



Meso Scale

Forest Composition

Soil Conditions

Transpiration, Evaporation

Climate

Topography

Micro Scale

from Luxmoore, King and Tharp (1991)

Figure 1
Relationship between Macro, Meso and Micro Conditions

neighbours influence how closely trees may be packed; at the micro level, the local soil conditions are the ultimate determinant of the capability of the site to support tree growth.

Increased competition for light requires increased height; increased height over the main canopy results in increased interception of wind. The result is a greater need for stabilization, which is offset by the benefits of increased photosynthesis. Photosynthesis may, in turn, be limited by restrictions in water, nutrients, metal toxicity and disturbance associated with the site. The ability to respond to soil conditions, competition and wind force are determined on a genetic basis, species-wise and individually.

The **stem-form/stand-closure/site-conditions** relationship is a component of tree allometry. Plant allometry is essentially plant geometry or dimensional relationships (King, 1991) and is both a reflection of plant evolution and a constraint to adaptation. At the broadest level, the **stem-form** of the tree is a reflection of the relationship between plants and the environment. At increasingly more restricted levels there is a reflection on adaptation, on biomechanical adaptation, on stem adaptation, on tree stem adaptation and on **stem-form** adaptation and wind. At the finest level, the **stem-form** of the tree is a reflection of the relationship between the **stem-form** of an individual tree, the **stand-closure** of the neighboring trees and the prevailing **site-conditions.**

1.1 Relationship Between Plants and Environment

The relationship between the manner in which plants grow and their environment has been examined as a part of diverse survival

strategies (Schulze *et al.*,1986; Givnish, 1986; Fisher, 1986). One of the first principles in plant growth and adaptation was initially defined in 1841 by Liebig as "the law of the minimum". In 1905, Blackburn refined the concept and described "limiting factors" (Salisbury and Ross, 1992 pg 557). At the most basic level, plant growth is governed by whatever is most deficient in the environment, be it water, nutrients or light. These deterministic factors are modified, possibly to the point of complete negation, by stochastic factors. Random events such as fire, geologic events and human and animal activity may have such an impact as to completely obscure the more deterministic relationship between plants and the environment. The relationships observed under controlled conditions with simplistic factors (in vitro) may not be observed under natural conditions (in vivo).

Under conditions of resource scarcity, survival involves maximizing the acquisition and minimizing the utilization of the limiting resource. The lack of water or nutrients may be a climatic or soil limitation or it may be a competitive problem if plant growth is extensive. A lack of light is very seldom a solar problem except seasonally in the polar areas; climatic conditions may cause sufficient obstruction of light to preclude the survival of some species. Usually, a lack of light is a competitive problem with taller plants shading lower plants to the point that understory species will not be able to photosynthesize sufficiently to meet the energy requirements to survive. The lack of ability to compete successfully for light is the driving mechanism behind the thinning of closed stands with time; ultimately, scarce resources are claimed by those individuals or species that are better able to

photosynthesize, thereby claiming a disproportionate share of the resources and further increasing their advantage.

The deterministic response to resource scarcity may be altered or obscured by stochastic factors. In the foothills of west-central Alberta, xeric sites are usually occupied by *Pinus contorta* Loudon (Lodgepole Pine) but *Populus tremuloides* Michx. (Trembling Aspen) may also be present instead of or in combination with *Pinus contorta*. *Pinus contorta* is better able to survive under dry conditions; it has a thick, corky bark, a deep tap root and waxy needles to prevent moisture loss. While deterministic factors would suggest that *Pinus contorta* should dominate on these sites, there are also stochastic factors involved, particularly where fire history is concerned. The intensity and frequency of repeated fires may influence the more deterministic effect of drought. In a mixed stand of *Populus tremuloides* and *Pinus contorta*, repeated light fires result in the proliferation of *Populus tremuloides*, a clonal species which can regenerate quickly from subterranian roots. Intense fires, especially ground fires, result in the destruction of the roots, allowing *Pinus contorta* to regenerate. In addition, *Pinus contorta* has serotinous cones which open in intense heat. Incineration of the duff provides the proper medium for germination and subsequent regeneration of *Pinus contorta*. While *Pinus contorta* may be better adapted in a deterministic manner, *Populus tremuloides* may actually dominate for stochastic reasons (Wright and Bailey, 1982 pg 19, 290, 300).

1.2 Adaptation

Plants adapt to the lack of light through various mechanisms; some are biochemical and some are biomechanical in nature.

Biochemical adaptation may take the form of hormone production to induce dormancy or early leaf flush to confer competitive advantage. Low light conditions that are seasonal may result in periods of dormancy. Plants which live in the understory have adapted biochemically by developing high concentrations of chlorophyll in the leaves, by directing carbohydrates into storage in roots, and by flushing early and beginning to photosynthesize before the deciduous overstory has acquired leaves. Biochemical adaptation may take the form of delayed sexual reproduction. In extreme conditions of light deficiency, seed production may be sacrificed in favour of vegetative spread.

Biomechanical adaptation involves changing plant structure to achieve the maximum efficiency in light capture and/or to reduce the light available to the competing plants. Leaf height, arrangement and shape may be altered to present the most cost-effective means of capturing light in any particular environment (Givnish, 1986).

1.3 Biomechanical Adaptation

Biomechanical adaptation in plants involves changing leaf structure, branch structure and stem structure; reproductive structures, although they are usually present on the plant for shorter periods of time, may be biomechanically adapted. Givnish (1986) examined forest herbs, the increased supporting structure (veins and stem) associated with increased photosynthetic area and the environment that different species occupied. He determined that there was a tradeoff between competition for height gain, and its associated photosynthetic advantage, and the increased cost of

allocating more carbon and energy to building more support structure.

For woody species, biomechanical adaptation is more complex than in herbaceous species due to the presence of perennial structures in the form of woody stems and branches. Leaves may also become short-lived perennial structures in evergreen species. The difference in leaf structure from a thin, flat, broad, deciduous type to a thicker, relatively narrower evergreen needle type is a biomechanical adaptation. The evergreen needle type of leaf has greater longevity; three years is the life expectancy of this type of leaf. In the harsh conditions and short growing season associated with tree-line, a reduced biomass investment in new leaves is an advantage; only needle-type evergreen species survive.

The woody structures of trees are particularly subject to selection pressure for biomechanical efficiency. Lignin is energy-expensive to produce; a tree which did not have mechanisms to strictly regulate the amount of photosynthate allocated to stem and branches would be at a competitive disadvantage. The geometry of branching patterns in relation to light interception and photo-synthetic efficiency was examined by Fisher (1986). While there is some plasticity in branching arrangements, the overall conformation of the tree structure is at least partially genetically determined and has developed as part of a set of survival mechanisms under a given set of environmental conditions. A broad mono-layer leaf canopy would be suitable for primary successional species; the same canopy would not intercept light as efficiently as the conical

multi-layer canopy characteristic of many secondary successional evergreen species.

1.4 Stem Adaptation

Plant height increase is accomplished through shoot elongation in response to competition for light. The **stem-form** is determined by the direction of growth of the apical bud; for a stem, the bud produces an erect and positively gravitropic shoot which, if undamaged, undergoes lignification and thickening (Fisher, 1986). The degree of lignification and thickening determine the strength and support for the foliage. In the competition for light among forest herbs and trees, greater height is associated with increased light capture and enhanced photosynthesis. There are exceptions to this rule. The forest herbs *Disporum* Salisb. (Fairy-bells), *Streptopus* Michx. and *Smilacina racemosa* (L.) Desf. (False Solomon's-seal) have developed an arching habit in the downslope direction, thus shading any erect species growing below and downslope (Givnish, 1986). Riverbank-adapted tree species have developed a horizontal response which confers a light interception advantage (Loehle, 1986).

For most tree species, the presence of an upright perennial supporting structure confers advantage in the competition within the forest for light. While a tall, vertical stem gives trees an undisputed advantage over other plant species in light interception, the investment in such a structure is high. It is estimated that a tree stem occupies 55 to 65% of the cubic volume of the complete tree, excluding foliage (Husch *et al.*, 1982). While photosynthesis is enhanced, substantial amounts of biomass

must be partitioned into the construction and maintenance of the stem.

1.5 Tree Stem Adaptation

For trees, up to 45% of the carbohydrate production may go into the production of wood (Kozlowski, 1962 pg 149). The photosynthetic gains achieved by further height growth must always be offset by the costs; directly, in terms of photosynthate expenditure to produce and maintain wood and indirectly as an increase in height over neighbouring trees. Over-topping the canopy exposes the individual tree more directly to the effects of wind, snow accumulation and temperature change. In addition, the ability of any individual tree to respond to the pressure for upward or outward growth is limited by the availability of resources and by the adaptations required to withstand severe stress that may be present as part of the ecosystem conditions.

An increase in woody structure is governed hormonally by biomass partitioning. Biomass partitioning is variable according to the environmental conditions. It is particularly affected by soil moisture levels, nutrient levels, pH and insect attack (Comeau and Kimmins, 1989; Waring and Pitman, 1985; Li *et al.*, 1991; Axelsson and Axelsson, 1986; Schindelbeck and Riha, 1988). Changes in the allocation of biomass may limit the ability of the tree to increase height or diameter. Comeau and Kimmins demonstrated that the order of biomass production allocation changes from stems > fine and small roots > foliage > coarse roots > branches under wet conditions to fine roots > stems > foliage > coarse roots > branches under dry conditions. Li *et al.* (1991) demonstrated an increase in relative biomass allocation to roots with low nitrogen

levels. The ability to respond to low nitrogen levels varied with differences in the genetics of the individual seedlings.

1.6 **Stem-form** and Wind Adaptation

The basis for examining the relationship between the form that a tree stem takes and the density of the stand lies in the effect of wind force on the stem. Theoretically, trees only reach 1/4 of their maximum potential height, the height at which a tree would buckle under its own weight (McMahon, 1973). Four theories have been developed to explain the configuration of the stem and the limitation on height. Timell (1986) has designated these as the nutritional, the water conduction, the mechanistic and the hormonal theories in his review of the subject. Two of these theories, the nutritional theory and the water conduction theory, are no longer considered to have any validity.

The nutritional theory advocates that stem growth occurs along the bole where nutrients are available. The water conduction theory suggests that the configuration of the stem exists to facilitate the movement of water from the roots to the crown. The mechanistic theory is based on the premise that the physical forces acting on the tree govern its shape. The hormonal theory states that the radial growth of a stem is determined by the presence of auxin and possibly growth inhibitors.

The most widely accepted theory is the mechanistic theory, although the explanation of the mechanisms may lie in the hormonal theory. The mechanistic theory was developed by Metzger in a series of papers from 1893 to 1908. This theory maintains that the shape of the tree is a compromise between a vertical gravitational

force which causes buckling and a horizontal force inflicted by wind (Timell 1986; Husch *et al.* 1982).

According to King (1986) wind is by far the over-riding factor; the weight of the stem does not become a factor until the tree is very large. The weight of the stem, however, may be influenced by the accumulation of snow and ice during the winter. Exposure to wind may be fairly gentle, as in wind sway, or catastrophic, as in toppling. Intermediate levels of wind force may knock the tree off the vertical axis producing lean and basal sweep. Wind sway has been associated with diameter increase; lean and basal sweep are rectified with reaction wood formation; uprooting often results in the death of the tree.

The amount of wind sway in a tree is affected by three main factors (Milne, 1991); 1) the interference of neighbouring branches 2) the aerodynamic drag of the foliage 3) the damping in the stem. The neighbourhood influences are governed by the nearest neighbour distances, the size of the neighbouring trees and the crown configuration of the neighbouring trees. The aerodynamic drag of the branches is a function of the form of the individual tree. Tree form includes factors such as branch bifurcation, conical/-rounded tree shape and an evergreen/deciduous habit. Environmental factors may act to modify the tree shape. Damage to the leafy tissues by ice-laden unidirectional winds results in the flagged form of *Picea engelmannii* Parry ex Engelm. (Engelmann Spruce) at treeline. The damping in the stem is linearly related to stem diameter (Milne, 1991) but it may also be a function of the structure of the wood composing the stem.

There are fundamental differences in the anatomy of the wood of angiosperms versus gymnosperms. In particular, there are differences in the reinforced structures that compose the xylem or water transport system. Gymnosperms possess only tracheids, which are narrow and discontinuous, for water conduction. Angiosperms possess both tracheids and broader, water-conducting vessels that extend the length of the tree (Salisbury and Ross, 1992 pg 99). Other anatomical differences arise due to environmental conditions. When a tree is vertically displaced, stabilization and restoration of a negative gravitropic response for the stem is achieved through the development of reaction wood; the type of reaction wood is different for angiosperms and gymnosperms. If an angiosperm is bent over, it will develop tension wood on the upper side of the stem; a gymnosperm will develop compression wood on the lower side (Kozlowski *et al*, 1991 pg 434). The presence of these two types of reaction wood differentially affect the flexibility in the stem. The requirement for flexibility in the stem may also be related to the root system stabilization. A poorly anchored tree requires more buttressing at the base to maintain an upright stance. Shallow-rooted trees, such as those occurring on thin soils or under conditions of high water table, are more subject to windthrow (Corns and Annas, 1984).

The relationship between wind, stem proportions and stand density was the basis of a study by Jacobs (1954). In a classic series of experiments with guyed trees over a period of 15 years, he examined the ratio of stem diameter to stem height, the stem volume, the root diameter increase near the tree base and eccentric growth of the stem. He demonstrated that free-swaying trees

developed an increase in diameter relative to height over stayed trees. This tapering effect was heightened when the stands were thinned.

Wind may be the causal agent in the development of stem taper but there are indications that the ability of the tree to respond is variable. While noting a relationship between stem taper and wind sway, Jacobs (1954) also noted that trees varied in their ability to respond to the stimulus provided by this movement and suggested the involvement of genetic factors specific to the sample tree and environmental factors specific to the site that the tree occupied. The configuration of the stem in response to wind sway may be a composite of genetics, climate, topography, competition, soil conditions and the random events that define the history of the stand.

Genetic differences are reflected in species differences in **stem-form** and species differences in the manner and degree to which wind force affects the taper. These differences may be the result of successional status, wood composition or crown configuration. As softwood is weak relative to hardwood, upward growth for a softwood would be more energy-expensive than for a hardwood. It would be expected that softwood trees would increase in diameter more rapidly than hardwood trees in order to stabilize the tree against buckling (Horn, 1971 pg 114). Differences in diameter increment have been associated with different species and changes in the distribution of foliage within the crown. Clyde and Titus (1987) determined that there were species differences between *Pinus contorta*, *Picea mariana* (Mill.) BSP. (Black Spruce) and *Picea glauca* (Moench) Voss (White Spruce) in the distribution of diameter

increment. *Picea glauca* is a secondary successional species; it is more shade-tolerant and retains its lower branches in contrast to *Pinus contorta*. Diameter increment does not decline as rapidly toward the tip for *Picea glauca;* the inherent **stem-form** is different as a result. Genetic factors are involved indirectly; tree species have inherent preferences/tolerances for **site-conditions** and the ability to respond to wind sway may be governed by the type of site occupied.

Climatic and topographic influences may be regional in nature; these are macro factors. Differences in **stem-form** for *Picea sitchensis* (Bong.) Carr. (Sitka spruce) have been noted by Farr *et al*. (1989) in response to changes in latitude. The more northerly the location, and presumably the less favourable the conditions, the greater the diameter relative to height. Daubenmire (1946) noted an increase in diameter relative to height with an increase in elevation. The higher the elevation, the colder the conditions and, in the case of sharply-ridged terrain, the greater the exposure to temperature extremes.

The competitive influences of other species early in stand establishment and of other overstory trees limits the water, nutrients and light available to any given tree; these are the meso factors. Penridge and Walker (1986) established that within stands of *Eucalyptus populnea* F., neighbouring trees do interfere with individual tree growth. The sizes of the individual neighbouring trees as well as their distance determines the degree of interference. The initially larger trees demonstrated greater girth increment as they were able to exploit more resources; the

advantage is constantly being magnified by greater photosynthetic gains.

The stand origins and initial competition may influence the **stem-form** well into maturity. Amateis and Burkhart (1987) demonstrated that trees originating in old field plantations exhibited less taper than trees originating from cutover sites. Trees in a naturally regenerated stand exhibited the most taper. This they attributed to the effect of increasing competition from other woody species; old field plantations have the least amount of this type of interference. While competitive influences early in stand establishment may have some influence, it should be noted that differences in inherent soil structure or fertility will also have an effect. Prolonged cultivation associated with old fields reduces the nutrients available for plant growth. Cutover plantations are associated with some nutrient loss and naturally regenerating stands after fire benefit from the initial release of nutrients. In addition, the loss of soil structure associated with cultivation reduces its moisture-holding capacity; the disturbance associated with timber harvest is also associated with the loss of tilth.

Soil conditions have been recognized as a major influence on tree growth and the ability to respond to wind sway; these are the micro factors. Soil drainage, nutrient status, pH and texture are considered to have a role in tree growth. The status of the rooting medium determines the nutrient and water status of the tree and also the stability of the stem. Halter *et al.* (1993) compared the growth and wind stability of 12 year old trees from naturally regenerated stands with containerized plantings. The planted

saplings displayed poorer root architecture and relatively less shoot growth than the natural saplings. The planted saplings displayed 15% basal sweep or toppling, the natural saplings displayed none. In his discussion on the radial growth of roots, Fayle (1968) noted that the loss of wind sway reduces growth in the basal areas of both stem and roots.

Stand history chronicles exposure to climatic variation and catastrophic events. The decrease in tree ring increment associated with drought has been recognized as a means of climate reconstruction where no records existed (Cook and Jacoby, 1977). Exposure to gale-force winds may not elicit a response that is a magnification of the response to a prevailing wind. Severe unidirectional winds will displace the tree from its vertical axis and cause the formation of reaction wood and eccentric growth as well as some basal thickening (Timell, 1986 pg 1344-1345).

1.7 **Stem-form, Stand-closure** and **Site-conditions**

Existing studies suggest that the **stem-form/stand-closure-/site-conditions** relationship should be a three-tiered hierarchical relationship. The **site-conditions** govern the germination and mortality within a given stand and result in the **stand-closure.** The **stand-closure** determines how the wind force is dispersed; whether a few trees are subjected to alot of wind sway or many trees are subjected to a little sway. The amount of wind sway determines the **stem-form;** more wind sway results in a more tapered tree. The **tree species** determines the response to **site-conditions,** the degree to which **stand-closure** is affected by wind force and the response of **stem-form** to wind sway. The clarity of this relationship may be affected by a number of factors:

1) the stand history may over-ride the deterministic influence of the **site-conditions**

2) the **site-conditions** may produce conditions of stress which limit the response of the **stem-form** to wind sway

3) the genetic characteristics of the **tree species** may produce a specific **stem-form** regardless of the **site-conditions** or the **stand-closure**

This study was designed to analyze the **stem-form/stand-closure/site-conditions** relationship and its component relationships, with consideration given to the manner that these relationships fit within the larger biological context.

2. DATA ACQUISITION

The raw data that were utilized in this study were collected previously under the Ecological Land Classification and Biogeoclimatic Classification programs, Resource Evaluation and Planning Division, Alberta Forestry, Lands and Wildlife. These data were acquired on tape and transferred to computer mainframe for analysis. The original data inventory was composed of four parts: environmental, vegetation, soils and timber. Modifications were performed on the original data in order that they be utilized in this study. These alterations are described for each of the four parts.

The original methodology for collection was designed to be detailed (intensive). These data were stratified and classified. A less detailed but compatible methodology for data collection was used to determine the aerial extent of the classifications. These two data sets were integrated and formed the basis from which land use decisions were made. All data were transferred from the tape but only those detailed sites with measurable trees were utilized in this study. This baseline information can be obtained on tape as SPSSx data sets (contact name and address in Appendix D).

2.1 Background

The Berland-Fox Creek study area is located in the foothills of west-central Alberta between approximately 53^0 40' and 54^0 50' N latitude and 116^0 10' and 119^0 00' W longitude. Figure 2 indicates the regional location and Figure 3 shows the extent of the study area. The survey covers an area of more than 10 000km^2. Fox Creek (population 2 000) and Grand Cache (population 5 000) are

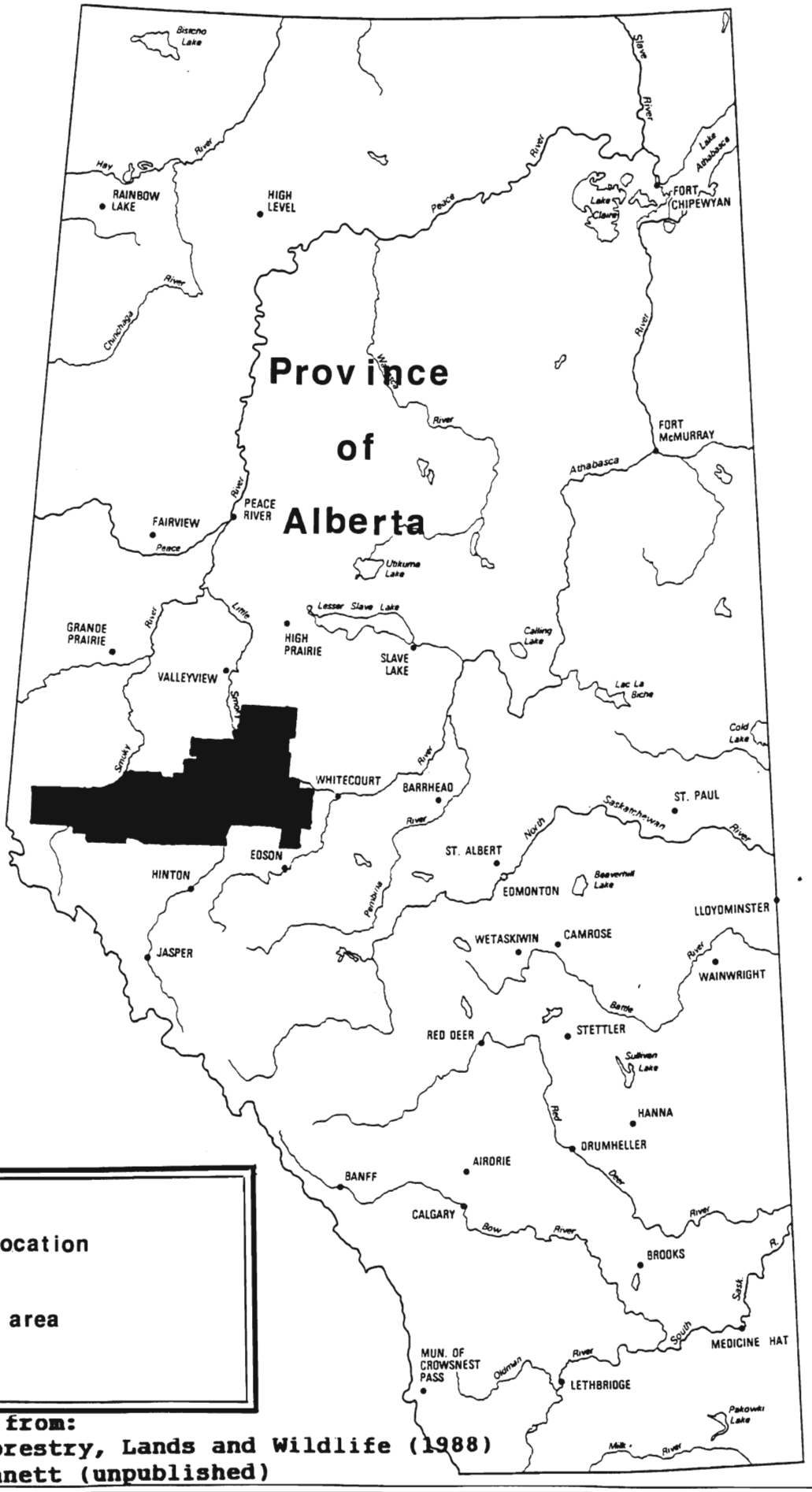
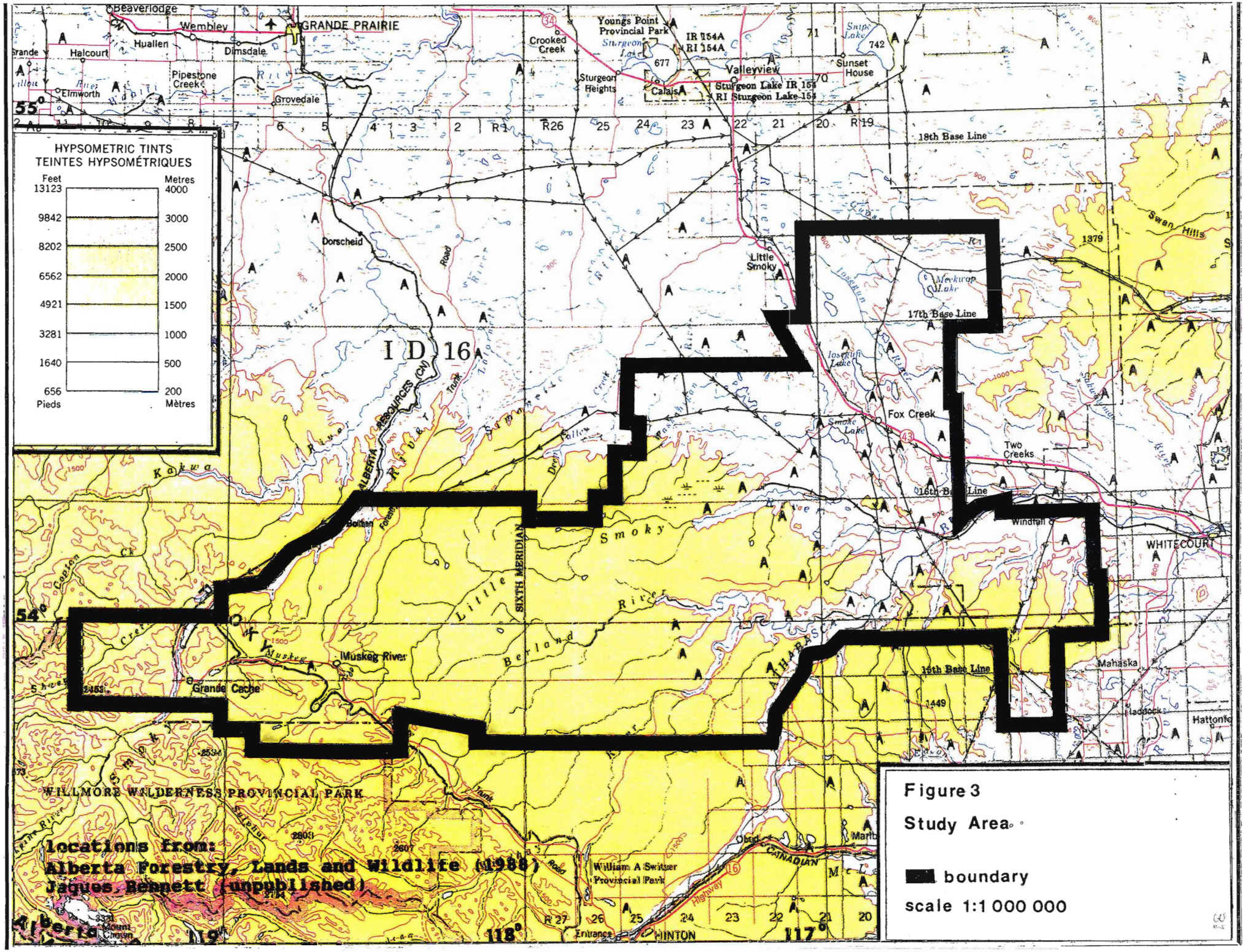


Figure 2

Regional Location

study area

locations from:
Alberta Forestry, Lands and Wildlife (1988)
Jaques Bennett (unpublished)

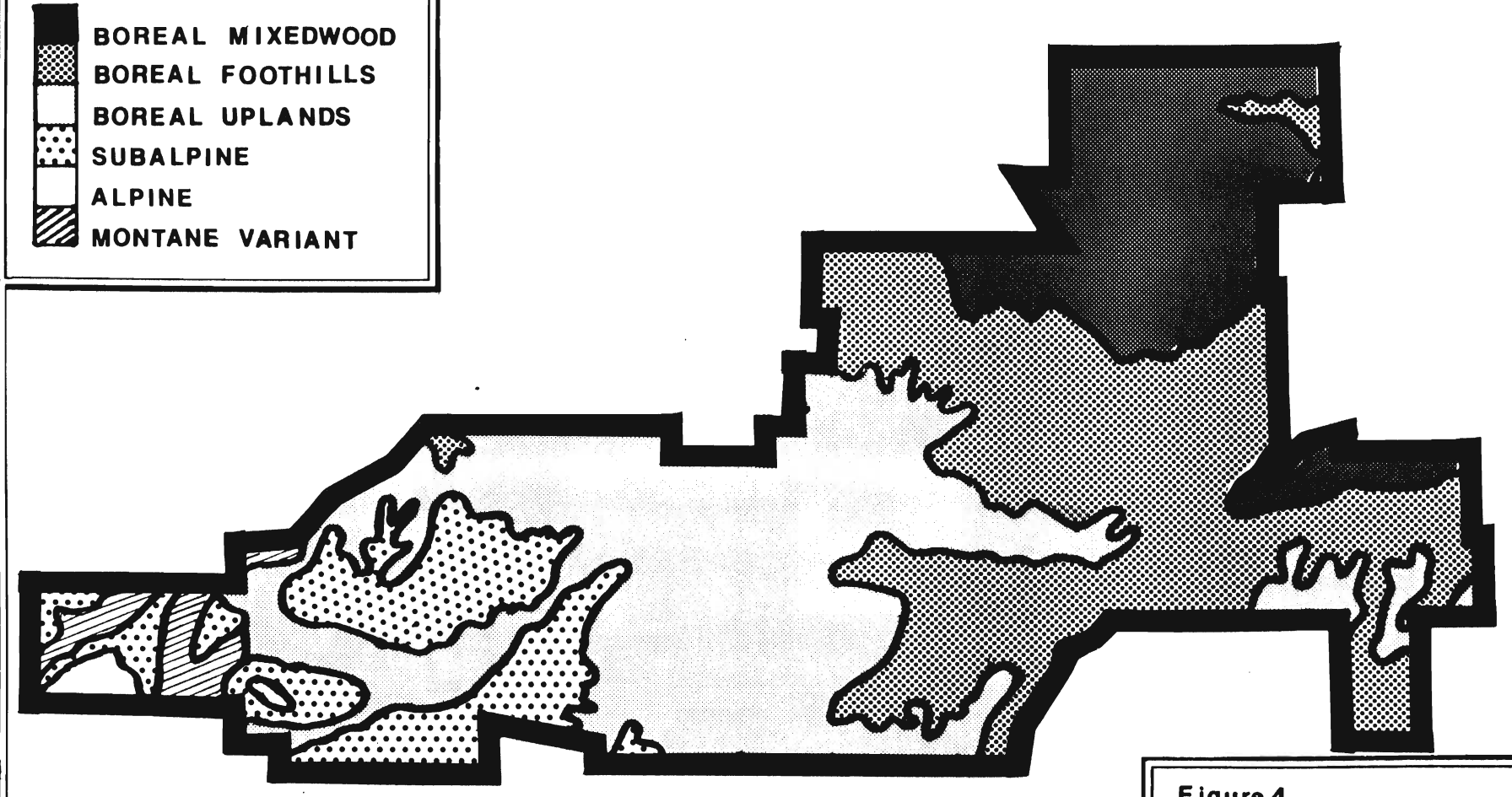

HYPSOMETRIC TINTS
TEINTES HYPSOMÉTRIQUES
Feet
Pieds
Metres
Mètres
13123
4000
9842
3000
8202
2500
6562
2000
4921
1500
3281
1000
1640
500
656
200
ID 16
GRANDE PRAIRIE
Beaverlodge
Wembley
Hythe
Halcourt
Dimsdale
Elmworth
Pipestone Creek
Grovedale
Crooked Creek
Youngs Point Provincial Park
IR 154A
RI 154A
Sturgeon Heights
Calais
Valleyview
Sturgeon Lake IR 154
RI Sturgeon Lake 154
Sunset House
Snipe Lake
742
677
18th Base Line
17th Base Line
16th Base Line
15th Base Line
Dorscheid
Road
Little Smoky
Swan Hills
1379
Meekwap Lake
Joseph Lake
Fox Creek
Smoke Lake
Two Creeks
Windfall
WHITECOURT
Kakwa
River
ALBERTA RESOURCES (CN) Trunk
Dunes Falls
Smoky
Little Berland River
SIXTH MERIDIAN
Muskeg River
Grande Cache
Mahaska
Haddock
Hattonford
WILLMORE WILDERNESS PROVINCIAL PARK
William A Switzer Provincial Park
CANADIAN
Highway 16
Entrance
HINTON
Alberta
55°
54°
119°
118°
117°
R1
R26
R27
R19
Figure 3
Study Area
boundary
scale 1:1 000 000
locations from:
Alberta Forestry, Lands and Wildlife (1988)
Jaques, Bennett (unpublished)

the only major settlements within the boundaries of the study area. Other towns in the vicinity include Hinton and Edson to the south, Whitecourt to the east, and Valleyview to the north.

The area had not been systematically logged prior to 1980 and cutting was confined to small areas at the time of data collection (1983 to 1986). British Columbia Forest Products (now Fletcher Challenge) had located a sawmill on the west side of the study area just outside of Grande Cache and was proceeding to log the area by clearcut. The original forest management agreement required that a pulp mill be built at Knight, south of Fox Creek. This plan has since been abandoned.

This area has been the focus of seismic exploration for petroleum and there are many cut lines and well sites. An old but producing oil and gas field, originally Hudson's Bay Oil and Gas and now Dome Petroleum, lies immediately south of Fox Creek. Gas processing plants are located throughout the eastern portion of the study area; a large operation is situated in the vicinity of Windfall.

There are major changes in elevation, topography and vegetation across the area, particularly from east to west. The elevation ranges from approximately 700masl in the east to 2000masl in the west. There are five ecoregions as defined by Strong and Leggatt (1981) plus a montane variant bordering the Smoky River (Figure 4). There are abundant fluvial sites; in addition to the Smoky, there are nine other rivers traversing or bordering the area. These include the Little Smoky, Berland, Athabasca, Wildhay, Muskeg, Simonette, Goose, Waskahigan and Iosegun Rivers.



locations from:
Alberta Forestry, Lands and Wildlife (1988)
Jaques Bennett (unpublished)
Strong and Leggatt (1981)

Figure 4.
Ecoregions

boundary
scale 1:1 000 000

Photograph 1 shows a fluvial area adjacent to the Athabasca River, below steep bluffs. The riparian vegetation is obviously quite variable; some of these sites are treed and some are disturbed frequently, resulting in meadows. The light coloured area adjacent to the river in the bottom left corner of the photograph is a highly disturbed silty or sandy site where few trees have been able to establish themselves. When present, tree species usually consist of *Picea glauca*, *Populus balsamifera* L. (Balsam Poplar) and *Populus tremuloides*. *Betula papyrifera* Marsh. (Paper Birch) is occasionally present in small pockets. The understory is characterized by *Salix* L. (Willow) and *Carex* L. (Sedge) and *Equisetum* L. (Horsetail) on the wettest sites and *Elymus innovatus* Beal (Hairy Wild Rye), *Delphinium glaucum* S. Wats. (Tall Larkspur), *Mertensia paniculata* (Ait.) G. Don. (Tall Mertensia) and *Thalictrum* L. (Meadow Rue) on the drier sites (Strong and Leggatt, 1981; Jaques Bennett, unpublished data; Kocaoglu and Jaques Bennett, 1983).

The southeastern portion of the area is of low relief (Photograph 2). It is characterized by vegetation of the Boreal Mixedwood Ecoregion (up to 850masl). Some disturbance, in the form of seismic exploration cutlines and test sites for oil and gas wells, is present. On modal sites, *Populus tremuloides* dominates the overstory with a variable understory. More open stands often have a dense shrub cover composed of *Rosa* L. (Rose), *Cornus stolonifera* Michx. (Red Osier Dogwood), *Salix bebbiana* Sarg. (Beaked Willow), *Amelanchier alnifolia* Nutt. (Saskatoon) and occasionally *Corylus cornuta* Marsh. (Beaked Hazelnut). Forbs and graminoids usually include *Lathyrus* Hook. (Peavine), *Vicia*

Photograph 1 (left)

Fluvial Ecoregion-
Athabasca River

Photograph 2 (below)

Boreal Mixedwood Ecoregion-
vicinity of Tom Hill Tower

L.(Vetch), *Epilobium angustifolia* L. (Willow-herb), *Elymus innovatus* and *Calamagrostis* Adans. (Reed Grass). Secondary succession is to *Picea glauca*. Xeric sites are occupied by *Pinus contorta* (Lodgepole Pine) with a sparse understory of *Vaccinium myrtilloides* Michx. (Blueberry) and *Cladina* and *Cladonia* (Reindeer Lichen). Wet, oligotrophic sites are occupied by *Picea mariana*, *Ledum groenlandicum* Oeder (Common Labrador Tea) and *Sphagnum* (Peat Moss). More eutrophic wet sites are occupied by *Larix laricina* (Du Roi) (Tamarack), *Betula glandulosa* Michx. (Dwarf Birch) and *Carex* (Strong and Leggatt, 1981; Jaques Bennett, unpublished data; Kocaoglu and Jaques Bennett, 1983).

The bulk of the study area in the southeast and centre is characterized by rolling uplands and plateaus (Photograph 3) with broad wetlands. Ecological conditions range from those characteristic of the Boreal Foothills Ecoregion (under 1200masl) to the Boreal Uplands Ecoregion (up to 1500masl). The vegetation of these two ecoregions is very similar; the major distinction between them is the presence of *Populus tremuloides* as part of the overstory of the Boreal Foothills. This region is composed of almost unbroken expanses of *Pinus contorta* and *Picea mariana* with *Picea mariana* dominating on the wettest sites and *Pinus contorta* dominating on the driest sites. The understory is consistently *Ledum groenlandicum*, *Linnaea borealis* L. (Twin-flower) and *Vaccinium myrtillifolia* with *Pleurozium schreberi/Hylocomium splendens/Ptilium crista-castrensis* (Feathermoss). Secondary succession is to *Picea glauca* but characteristics of *Picea engelmannii* begin to appear in *Picea glauca* present in the Boreal Uplands (Strong and Leggatt, 1981; Jaques Bennett, unpublished data).

Photograph 3 (left)

Boreal Foothills and
Boreal Uplands Ecoregions
-Berland River

Photograph 4 depicts the northwestern portion of the study area. This is a region of broad, flat, high elevation plateaus with the Boreal Uplands Ecoregion at the base (below 1500masl) grading to the Subalpine Ecoregion at the top. There is less disturbance from oil and gas exploration than the eastern portion of the study area. Some areas have been clearcut, as evident from the photograph. *Pinus contorta* with *Abies lasiocarpa* (Hook.) Nutt. (Alpine Fir) and *Picea engelmannii* dominate the overstory in the Subalpine. Soil moisture excess or deficiency is not common and cool moist conditions prevail. *Picea mariana* is largely absent and *Populus tremuloides* has disappeared as a component of the overstory. The understory vegetation is a distinctive combination of *Menziesia ferruginea* J.E. Smith (False-azalea), *Rhododendron albiflora* Hook. (White-flowered Rhododendron), *Vaccinium membranaceum* Dougl. ex Hook. (Tall Bilberry) and *Pleurozium schreberi/-Hylocomium splendens/Ptilium crista-castrensis* (Strong and Leggatt, 1981; Jaques Bennett, unpublished data).

Photograph 5 shows the Montane variant along the Smoky River in the foreground and the Rocky Mountain Foothills in the background. The Montane variant has vegetation similar to that of the Montane Ecoregion but is too far north to support *Pseudotsuga menziesia* Carr. (Douglas-fir). This is the only area where *Populus tremuloides* was found at elevations above 1500masl. These sites are treeless or sparsely treed and are characterized by warm, dry conditions with *Rosa*, *Arctostaphylos uva-ursi* Adans. (Bearberry), *Elymus innovatus*, *Achillea millefolium* L. (Common Yarrow) and *Cladina* and *Cladonia* (Jaques Bennett, unpublished data).

Photograph 4 (above)

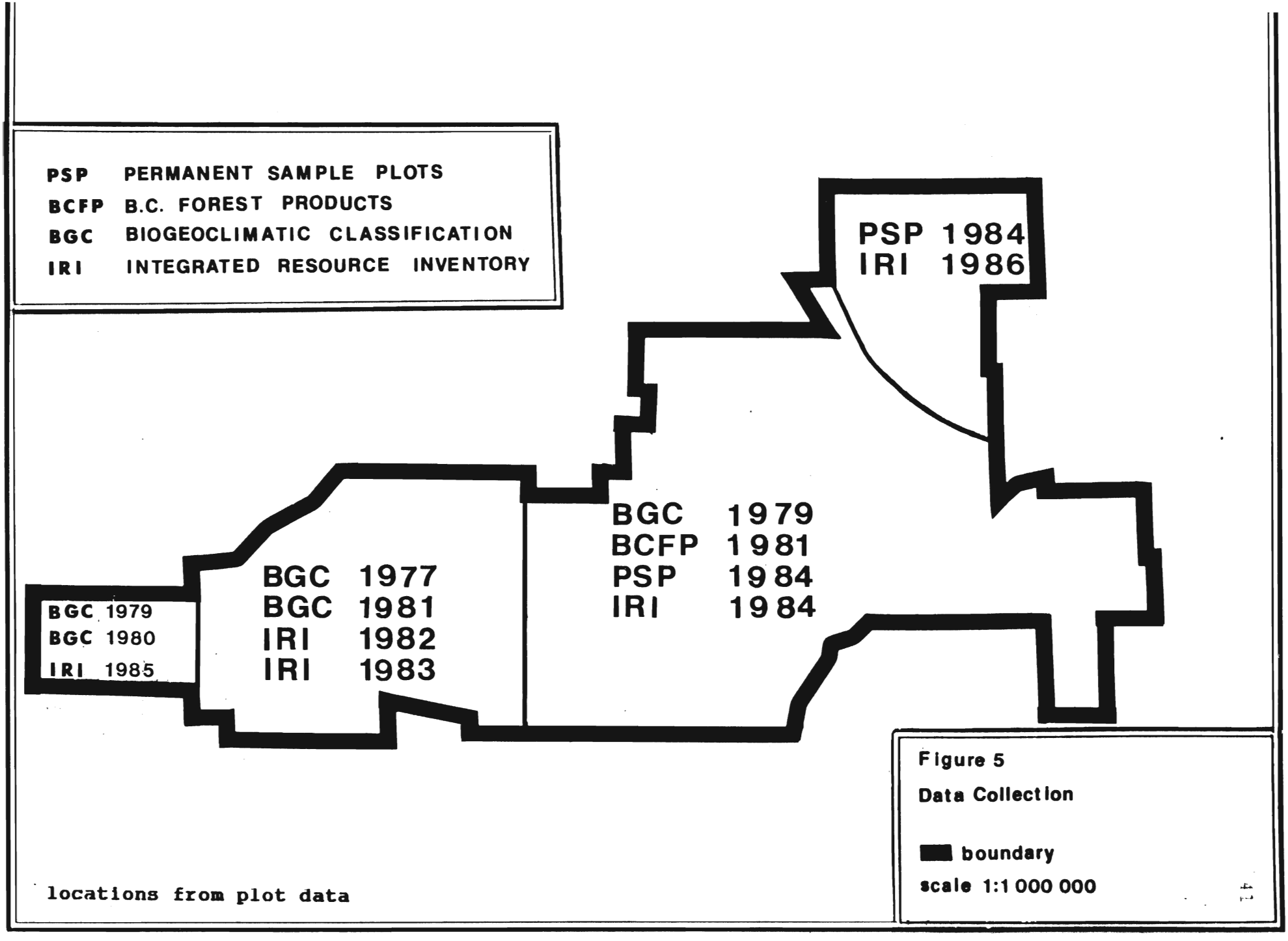
Boreal Uplands and Subalpine Ecoregions-region near Smoky and Kakwa Rivers

Photograph 5 (above)

Montane, Subalpine and Alpine Ecoregions-Rocky Mountain Foothills Foothills near Smoky River

The southwestern portion of the study area appears as the background in Photograph 5. The elevations in the foothills may be in excess of 2000masl. It is characterized by well defined exposed peaks, which may be above treeline, and deep cold valleys. The treeless Alpine Ecoregion is present above 1900masl. The characteristic vegetation of the Alpine Ecoregion is composed of *Dryas* L. (Dryad), *Saxifraga* L. (Saxifrage), *Aconitum delphinifolium* DC (Monkshood), *Gentiana* L. (Gentian), *Kobresia myosuroides* Willd. (Bog Sedge), *Poa alpina* L. (Alpine Bluegrass) and *Cladina* and *Cladonia*. There is a transition zone of stunted flagged *Picea englemannii* and *Abies lasiocarpa* known as krummolz between treeline and the Subalpine Ecoregion (Strong and Leggatt, 1981; Jaques Bennett, unpublished data).

Data collection by Alberta Forestry Lands and Wildlife was begun in 1977, with the major portion of the data collected between the years of 1983 and 1986 (Figure 5). The initial sampling of the area was done in 1977, 1979 and 1981 under the Biogeoclimatic Classification program, a co-operative program between the Resource Evaluation and Planning division and the Forestry Research branch within Alberta Forestry Lands and Wildlife. The mandate of the Biogeoclimatic Classification program was to establish the relationship between the **site-conditions** and forest productivity. All of the 49 plots established under this program were utilized in the analysis for this thesis. The methodology utilized in biogeoclimatic classification was drawn from a number of sources and was summarized in Alberta Forestry, Lands and Wildlife (1985),


PSP PERMANENT SAMPLE PLOTS
BCFP B.C. FOREST PRODUCTS
BGC BIOGEOCLIMATIC CLASSIFICATION
IRI INTEGRATED RESOURCE INVENTORY
PSP 1984
IRI 1986
BGC 1979
BCFP 1981
PSP 1984
IRI 1984
BGC 1977
BGC 1981
IRI 1982
IRI 1983
BGC 1979
BGC 1980
IRI 1985
Figure 5
Data Collection
boundary
scale 1:1 000 000
locations from plot data

which was published after data collection for this area was complete.

In 1981, a biogeoclimatic classification survey of the area was undertaken by British Columbia Forest Products on the eastern half of the area. There were 123 sites initially surveyed. As raw timber data were not available for these sites, 19 plots were re-surveyed in 1984. Only data from these 19 sites were directly analyzed in this thesis; the other 104 sites were used in developing the **plant association** and **ecoregion** classifications.

In 1984, the permanent sample plots established by Alberta Forestry were surveyed utilizing a biogeoclimatic classification methodology. As the raw timber data were not available, the data from these plots were not utilized directly in the analysis for this thesis. These data were used in developing the **plant association** and **ecoregion** classifications for the study area.

The bulk of the data available for the study area were collected between 1983 and 1986 under the Integrated Resource Inventory program with the Resource Evaluation and Planning division of the Alberta government. As the collection methodology for many of these sites was not detailed, only data from 143 plots of the total surveyed were utilized directly in the analysis for this thesis.

In all of the data collection programs, random sampling was not employed in the selection of sites. Instead, site selection was designed to cover the variation within the study area. The area was first stratified by **ecoregion**, then by **parent material** and then by forest cover; sites were selected within each stratum with as wide an elevational and geographic distribution as access would

allow. In this manner, all possible combinations of overstory growing under all possible conditions would be sampled. Selected variables from the environment, vegetation, soils and timber data for a total of 653 samples from these sites were used in the analysis for this thesis. The variables used, the methodologies employed and the revisions utilized are outlined in the following sections.

2.2 Environmental Data

The environmental variables extracted from the database and utilized in this study are as follows:

Elevation (metres above sea level)

Slope (percent)

Aspect (degrees)

Surface cover (percent cover)

Ecological moisture regime

Ecological nutrient regime

Ecoregion

Elevation, slope, aspect, surface cover, ecological moisture regime and **ecological nutrient regime** were collected according to the methodology outlined in Alberta Forestry, Lands and Wildlife (1985).

Ecoregion was determined using a classification system outlined in Strong and Leggatt (1981) with two revisions. Strong and Leggatt mapped six categories for this area, including the alpine, subalpine, boreal uplands, boreal foothills and boreal mixedwood **ecoregions.** Data analysis by Alberta Forestry, Lands and Wildlife resulted in the inclusion of two more **ecoregions**, the fluvial and montane variant **ecoregions.**

Fluvial plots were given a separate designation by Alberta Forestry, Lands and Wildlife. In terms of soils, vegetation and climate, sites proximal to rivers were collectively similar and displayed little affinity to the vegetation of the **ecoregions** of the adjacent areas.

A montane variant was established by Alberta Forestry, Lands and Wildlife to describe the distinct climatic conditions in the Smoky River valley. Although the study area is north of the range of *Pseudotsuga menziesii*, aerial photography revealed the presence of high-elevation *Populus tremuloides*, brush and grasslands; this is vegetation characteristics of warm, dry montane areas, as described by Strong and Leggatt (1981).

2.3 Vegetation Data

The vegetation variables extracted from the database and utilized in this study are as follows:

Plant species

Vegetation layers (percent cover)

Plant association

Baseline information on individual **plant species** and **vegetation layers** was collected according the methodology outlined in Alberta Forestry, Lands and Wildlife (1985). **Plant species**, other than tree species, were not included directly in the analysis; they were used for classification purposes in defining the **plant associations.**

Plant species data were sorted and stratified by Alberta Forestry, Lands and Wildlife. The stratification was initially by **ecoregion**, secondly by overstory species and finally by the **site-conditions.** As these **plant associations** were designed to be mapped

at a scale of 1:50,000, the designations were fairly coarse. The **plant association** was defined and described by dominant and minor species. Dominant species were present in at least 60% of the plots (preferably 80%) with a mean cover of at least 10%. Minor species were present in at least 60% of the plots but do not achieve a mean cover of at least 10%. A brief description of the **plant assocations** is given in Appendix A. Full descriptions and accompanying productivity data are available in Vegetation Classification of the Berland-Fox Creek (Jaques Bennett, unpublished).

2.4 Soils Data

The soils variables extracted from the database and utilized in this study are as follows:

Soil pH

Soil Texture

Coarse Fragments (%)

Solum Thickness (cm)

Organic Layer Thickness (cm)

Soil Drainage

Soil Classification

Soil horizons were described according the methodology outlined in the Alberta Forestry, Lands and Wildlife (1985). Data on **soil pH, soil texture** and **coarse fragments** for the B horizon was utilized; data from the C horizon was used if the B horizon had not yet developed. The B horizon was selected to represent the rooting zone. The conditions in the rooting zone would have the most influence on tree growth.

The soil profile was classified by Alberta Forestry, Lands and Wildlife according to Agriculture Canada (1987) to the level of soil subgroup.

2.5 Timber Data

The timber variables extracted from the database and utilized in this study are as follows:

Tree Species

Crown Class

Tree Diameter

Tree Height

Tree Age

The timber variables extracted from the database, summarized as site variables and utilized in this study are as follows:

Total Volume

Total Basal Area

Total Live Stems

Total Dead Stems

Information on individual trees was collected according the methodology outlined in Alberta Forestry, Lands and Wildlife (1985). The information on individual trees was sorted and tallied as plot totals for basal area, volume, number of live stems and number of dead stems utilizing a tree mensuration program (Appendix D) adapted from a program developed for Alberta Forestry Lands and Wildlife.

In selecting the sample trees for analysis, only dominant and codominant trees were included. This was dictated by the need to control for differences in wind effects between over- and understory trees.

The conditioning effects (wind in this case) increase toward the top of the tree (Newberry *et al*, 1989). Understory trees are sheltered from the main effects of the wind, as the top of the tree is below the main canopy, where the wind effects would be most pronounced. Clyde and Titus (1987) observed that differences in diameter increases occurred between different crown classes of trees within the same stand. Dominant trees are subject to the most wind sway and produce the most diameter increase relative to height (King, 1990).

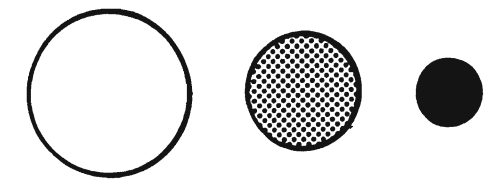
Codominant trees were included as sample trees for analysis. Some stands, particularly primary successional stands with *Pinus contorta* and *Populus tremuloides*, are often structured without dominant trees; it was necessary to include codominants to obtain a full range of **site-conditions**.

3. ANALYSIS

The statistical design of this study was constructed to analyze the **stem-form/stand-closure/site-conditions** relationship. This relationship can be summarized as eight potential outcomes (2^3). These are depicted in Figure 6. These outcomes list all possible combinations of the three components of the **stem-form/-stand-closure/site-conditions** relationship. The three component relationships are the **stand-closure/site-conditions** relationship, the **stem-form/site-conditions** relationship and the **stem-form/stand-closure** relationship. The implications of these eight outcomes are summarized in Table 1. These relationships can be summarized as predictive and not predictive.

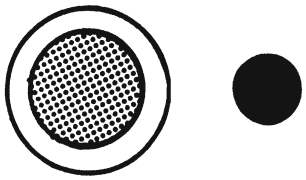
The **stand-closure/site-conditions** relationship can be summarized as predictive for four outcomes and not predictive for four outcomes. In outcome #2, outcome #4, outcome #6 and outcome #8, a change in the **site-conditions** produces a change in the **stand-closure.** In outcome #1, outcome #3, outcome #5 and outcome #7, a change in the **site-conditions** does not produce a change in the **stand-closure.**

The **stem-form/site-conditions** relationship can be summarized as predictive for four outcomes and not predictive for four outcomes. In outcome #4, outcome#5, outcome #6 and outcome #8, a change in the **site-conditions** produces a change in the **stem-form.** In outcome #1, outcome #2, outcome #3 and outcome #5, a change in the **site-conditions** does not produce a change in the **stem-form.** The **stem-form/stand-conditions** relationship can be summarized as predictive for four outcomes and not predictive for four outcomes.



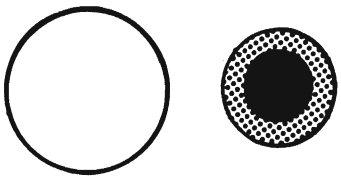
Outcome 1

No Stand-closure/Site-conditions Relationship
No Stem-form/Site-conditions Relationship
No Stem-form/Stand-closure Relationship



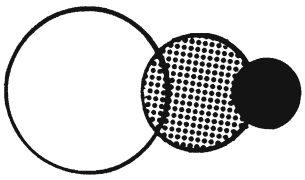
Outcome 2

Stand-closure/Site-conditions Relationship
No Stem-form/Site-conditions Relationship
No Stem-form/Stand-closure Relationship



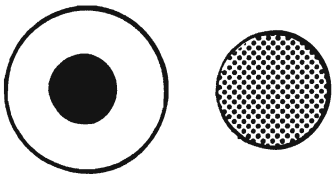
Outcome 3

No Stand-closure/Site-conditions Relationship
No Stem-form/Site-conditions Relationship
Stem-form/Stand-closure Relationship



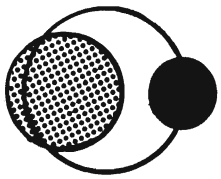
Outcome 4

Stand-closure/Site-conditions Relationship
No Stem-form/Site-conditions Relationship
Stem-form/Stand-closure Relationship



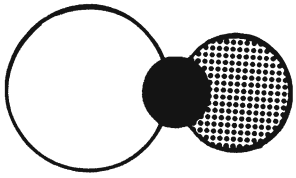
Outcome 5

No Stand-closure/Site-conditions Relationship
Stem-form/Site-conditions Relationship
No Stem-form/Stand-closure Relationship



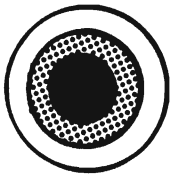
Outcome 6

Stand-closure/Site-conditions Relationship
Stem-form/Site-conditions Relationship
No Stem-form/Stand-closure Relationship



Outcome 7

No Stand-closure/Site-conditions Relationship
Stem-form/Site-conditions Relationship
Stem-form/Stand-closure Relationship



Outcome 8

Stand-closure/Site-conditions Relationship
Stem-form/Site-conditions Relationship
Stem-form/Stand-closure Relationship

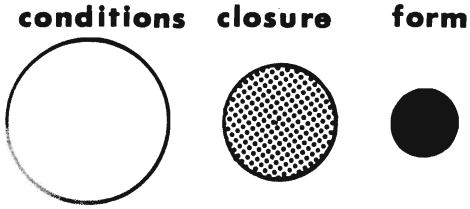


Figure 6

Venn Diagrams of Stem-form / Stand-closure / Site-conditions Relationships

Table 1

STEM–FORM/STAND–CLOSURE/SITE–CONDITIONS RELATIONSHIPS

OUTCOME #1	*independent variable*	
dependent variable	**STAND–CLOSURE**	**SITE–CONDITIONS**
STAND–CLOSURE		no
STEM–FORM	no	no

OUTCOME #2	*independent variable*	
dependent variable	**STAND–CLOSURE**	**SITE–CONDITIONS**
STAND–CLOSURE		yes
STEM–FORM	no	no

OUTCOME #3	*independent variable*	
dependent variable	**STAND–CLOSURE**	**SITE–CONDITIONS**
STAND–CLOSURE		no
STEM–FORM	yes	no

OUTCOME #4	*independent variable*	
dependent variable	**STAND–CLOSURE**	**SITE–CONDITIONS**
STAND–CLOSURE		yes
STEM–FORM	yes	no

OUTCOME #5	*independent variable*	
dependent variable	**STAND–CLOSURE**	**SITE–CONDITIONS**
STAND–CLOSURE		no
STEM–FORM	no	yes

OUTCOME #6	*independent variable*	
dependent variable	**STAND–CLOSURE**	**SITE–CONDITIONS**
STAND–CLOSURE		yes
STEM–FORM	no	yes

OUTCOME #7	*independent variable*	
dependent variable	**STAND–CLOSURE**	**SITE–CONDITIONS**
STAND–CLOSURE		no
STEM–FORM	yes	yes

OUTCOME #8	*independent variable*	
dependent variable	**STAND–CLOSURE**	**SITE–CONDITIONS**
STAND–CLOSURE		yes
STEM–FORM	yes	yes

In outcome #3 and outcome #8, a change in the **stand-closure** produces a change in the **stem-form;** greater wind force produces a change in taper. In outcome #4 and outcome #7, a change in **stand-closure** produces a change in **stem-form** but there are other factors involved. In outcome #1, outcome #2, outcome #5 and outcome #6, a change in the **stand-closure** does not produce a change in the **stem-form;** the wind force does not affect the taper.

Data analysis was performed on raw environmental, vegetation, soils and timber data (text files), utilizing a Fortran tree mensuration program (Appendix D) and SPSSx statistical programs (Appendix D). The raw data and the tree mensuration program were acquired on tape from Alberta Forestry, Lands and Wildlife, Land Information Services Division, Resource Information Services/Land Information Branch. The programming guidelines for SPSSx statistical programs are outlined in SPSS Inc.(1988). The raw data were off-loaded from tape, the plot totals for timber were generated from the tree mensuration program and SPSSx system files were generated to be used in further analysis. SPSSx programs were written to analyze the data in SPSSx system files.

The analysis procedure was composed of eight successive steps. These are summarized in a flow chart (Figure 7). Completion of each step was required before the next step could be initiated. For some steps, the results determined the procedure from that point onward. The eight analysis steps with alternative procedures are outlined as follows. Detailed descriptions of the statistical tests utilized are presented in Appendix C.

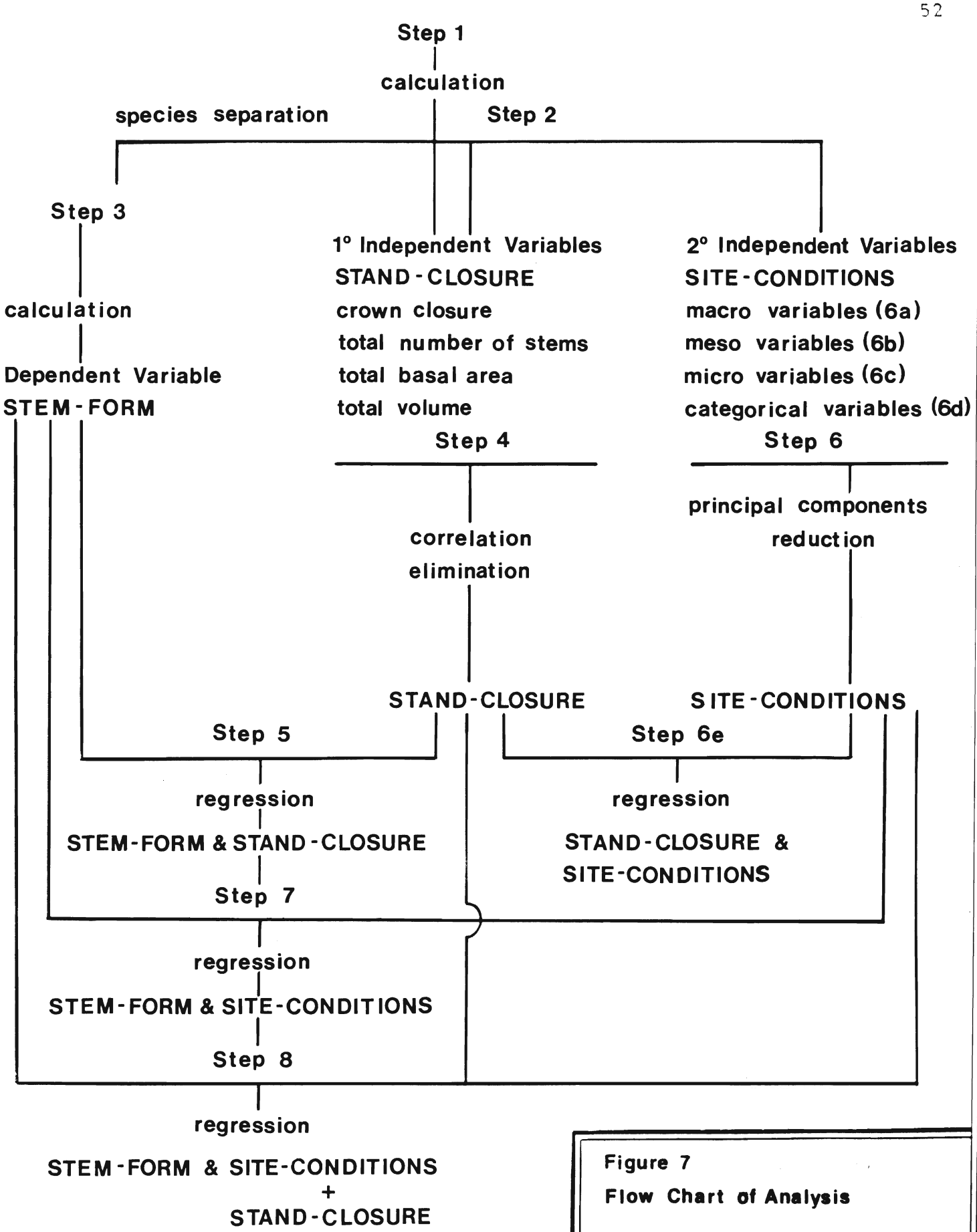


Figure 7
Flow Chart of Analysis

3.1 **Stand-closure** Calculation (Step 1)

Stand-closure is the density of the forest stand surrounding the sample trees. It may be represented by several variables: **crown closure, total number of stems, total basal area, total volume**, relative density, stand density index, tree-area ratio, crown competition factor, point density and forest stocking (Husch *et al.*, 1982 pg 328). There were four **stand-closure** variables that were utilized in this study: **crown closure, total number of stems, total basal area** and **total volume.**

Crown closure is a measure of the canopy closure. It is an indication of the amount of light that penetrates the canopy and reaches the forest floor. It was tallied as a visual estimate in the environmental data and was expressed as percent cover.

Total number of stems is the density of standing stems, including standing dead stems. A fallen dead tree, with the stem in contact with the ground was not included in the tally. It represents a count of trees per hectare. **Total number of stems** (live plus dead standing stems) was a plot total that must be calculated from the raw timber data.

Total basal area is the area of live wood. It was a plot total that was calculated from the raw timber data by the following equation and expressed at m^2 ha^{-1}:

$$ba = (pi\ (dbh/2)^2)10000$$

dbh = diameter at breast height (1.3m)

Total volume is the volume of live wood. It was a plot total that was calculated from the raw timber data by the following equation and expressed as m^3 ha^{-1}:

$$vol = A\ (dbh^B)\ (ht^C)$$

dbh = diameter at breast height (1.3m)

ht = total tree height from air-soil interface

A, B, C = species volume sampling region coefficients allows for tree bole variation by species and region (Alberta provincial standards, tree mensuration program, Appendix D)

The raw timber data were sorted and tallied plotwise by **tree species** utilizing the tree mensuration program, a Fortran program developed by Alberta Forestry, Lands and Wildlife, which was condensed and adapted to this study. The study area includes two Alberta Forest Service Volume Sampling Regions, VSR4 and VSR5 (Vegetation of the Berland - Fox Creek Areas, unpublished). In order to consistently examine the relationship between **stand-closure** and **stem-form**, a single set of province-wide VSR coefficients was incorporated into the timber mensuration program to calculate volume (Appendix D).

The variables representing different measures of **stand-closure** are all-species plot totals.

Crown closure (% cover)

Total basal area (m^2 ha^{-1})

Total stem volume (m^3 ha^{-1})

Total number of stems (stems ha^{-1})

3.2 Species Separation (Step 2)

Sample trees and their accompanying environmental, vegetation, soils and timber data (calculated in Step 1) were stratified by **tree species** into nine data sets (SPSSx system files). These represent the eight **tree species** present in the area plus one all

species data set. The **tree species** present in this area are as follows:

Pinus contorta

Picea mariana

Picea engelmannii x glauca

Abies lasiocarpa

Larix laricina

Populus tremuloides

Betula papyrifera

Populus balsamifera

Picea engelmannii x glauca was treated as one species as there were inseparable intergrades between *Picea glauca* and *Picea engelmannii*. The inclusion of a data set for all species served to verify **tree species** differences in **stem-form.**

3.3 **Stem-form** Calculation (Step 3)

The conformation of a tree stem is depicted in Figure 8. This is a representation only; the true conformation of the stem is very individual (Husch *et al.*, 1982). The actual form of the stem is a composite of the equations relating to a cylinder, paraboloid, cone and neiloid. Changes in form not only relate to changes in the diameter to height ratio but also to changes in overall shape.

A simple representation of **stem-form** has been employed for this study. **Stem-form** or taper has been represented by the ratio of diameter at breast height to total stem height. Diameter at breast height has been shown to adequately reflect basal thickening (Jacobs, 1954; Amateis and Burkhart, 1987). An increase in diameter relative to height would indicate increased stem taper.

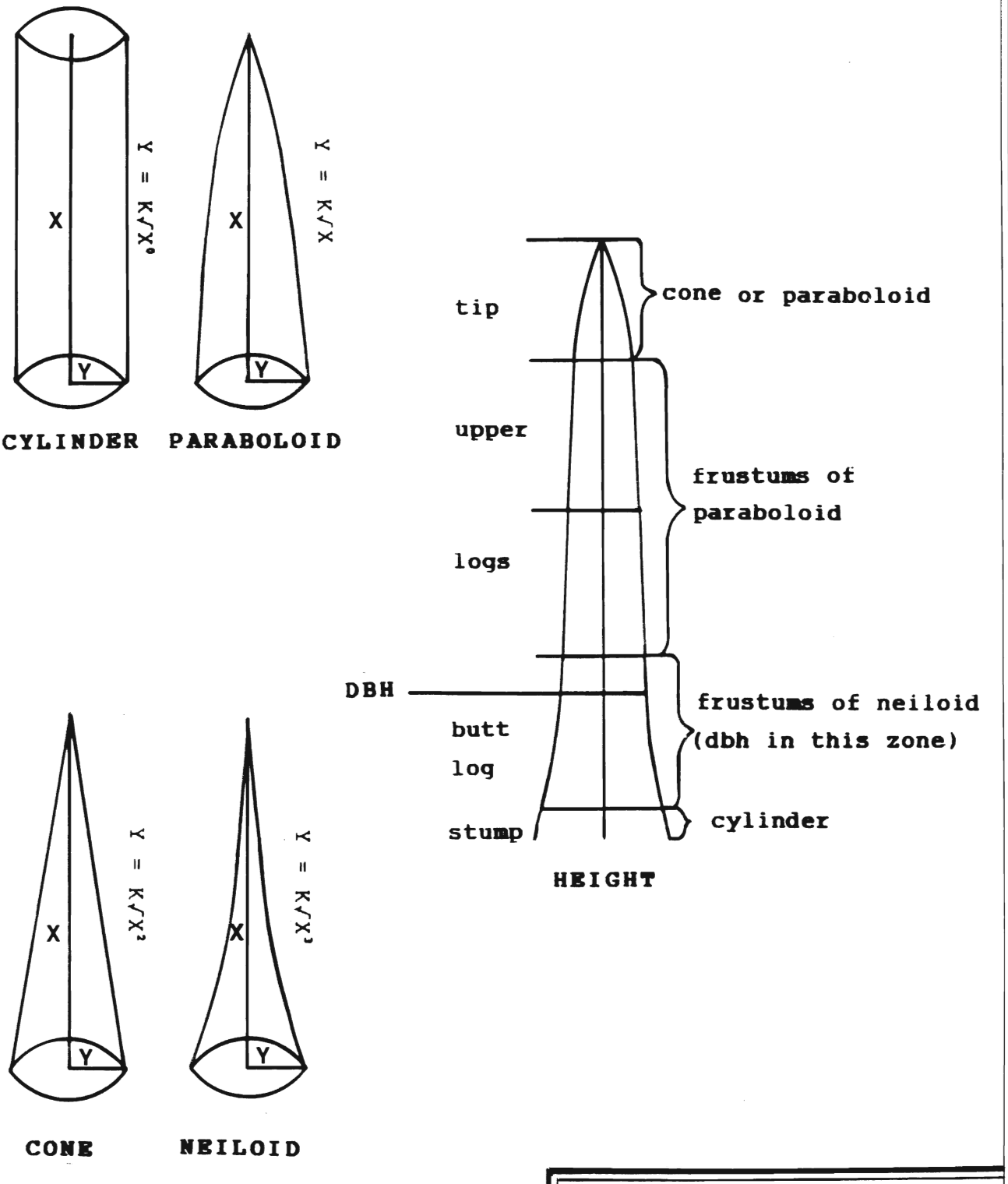


Figure 8

Stem-form Configuration

Husch *et al*, 1982 pg 100

The **stem-form** was calculated for each sample tree; it is expressed as the diameter at breast height to total height ratio. An analysis of variance (Appendix C2) was performed on the species data sets (Step 2) for the **stem-form** data to verify that there were species differences. The data distributions for each **tree species** were examined for skewness and kurtosis (Appendix C1) and transformations (Appendix C1) were performed to determine the best fit to a standard normal distribution. Transformations were performed unilaterally to facilitate **tree species** comparisons. Tests for homogeneity of variance (Appendix C2) were performed to determine if nonparametric or parametric procedures (Appendix C2) should be used to examine **tree species** differences in **stem-form.**

3.4 **Stand-closure** Variables Elimination (Step 4)

The data distributions for the variables representing **stand-closure** (calculated in Step 1) were examined for skewness and kurtosis (Appendix C1) to determine if transformation was necessary to achieve a normal distribution. Transformations (Appendix C1) were performed unilaterally to facilitate **tree species** comparisons. The variables were then examined to determine if **crown closure, total basal area, total volume** and **total number of stems** are highly correlated. If the absolute value of the correlation coefficient (Appendix C4) for any pair of these variables was 0.950 or greater, one of the pair of variables was eliminated from further analysis.

3.5 **Stem-form/Stand-closure** Relationship (Step 5)

The analysis for a **stem-form/stand-closure** relationship included only the uncorrelated **stand-closure** variables (Step 4). The data from the sample trees were analyzed to determine if the

correlation coefficients (Appendix C4) for the **stem-form/stand-closure** relationship were significantly different from 0.000.

The absolute value of the correlation coefficients for the **stem-form/stand-closure** relationship were examined to determine if the value was 0.950 or greater. If a value of 0.950 or greater existed then no further analysis was necessary.

3.6 **Stand-closure/Site-conditions** Relationship (Step 6)

If a correlation coefficient with an absolute value of 0.950 or greater was not achieved for the **stem-form/stand-closure** relationship (Step 5), an analysis of the **stand-closure/site-conditions** relationship was undertaken.

Site-conditions refer to those environmental variables related to growing conditions. Husch *et al.*(1982 pg 276) stratified these conditions into four categories: climatic factors (air temperature, precipitation, wind and insolation), topographic characteristics (**slope**, **elevation** and **aspect**), competition (influence of other trees, lesser vegetation and animals) and soil factors (physical and chemical characteristics, moisture and micro-organisms). For this study, the **site-conditions** variables have been grouped into macro, meso and micro variables. Macro variables correspond to a combination of climate and topography; topographic characteristics usually influence the climatic conditions. These are the general characteristics that correspond to areal measurements in the order of 10 to 100 hectares. Meso variables correspond to the competitive influences of other trees. These are the neighbourhood characteristics that correspond to areal measurements in the order of 0.01 to 1.00 hectares (100 to 10 000 m^2). The micro variables represent a combination of soil variables and understory vegeta-

tion. As these are not pioneer stands, the influence of the understory vegetation is not as much competitive as it is a reflection of soil conditions. These are the local characteristics that correspond to areal measurements in the order of 1 to 10 m^2.

There were no variables that are related to disturbance, consequently there were no measures of the influence of stochastic factors. It was not within the scope of this study to establish the degree to which stochastic factors over-ride deterministic factors. Stochastic factors involving random events in the stand history may have obscured the **stem-form/stand-closure/site-conditions** relationship.

Preliminary stratification and analysis of the **site-conditions** variables was performed to reduce the large number of variables and eliminate the possible problems associated with multicollinearity (Tabachnick and Fidell, 1989 pg 87-88). The **site-conditions** variables were separated into four groups, macro, meso, micro and categorical. Transformations (Appendix C1) were performed unilaterally on these variables. It should be noted that transformations were performed to improve the multiple correlation coefficients; they were not a requirement for regression analysis. The groups of variables were analyzed as follows:

3.6.1 Macro Variables (Step 6a)

Macro variables were topographic, with associated climatic differences. **Aspect** could not be utilized in its raw form and was converted to percent. **Slope** and **aspect** were reworked into four variables, **north effect**, **east effect**, **south effect** and **west effect** to reflect the inter-relationship and overall effect of topographic position.

Elevation

Slope

North Percent = 100(North Aspect x .5556)

East Percent = 100(East Aspect x .5556)

South Percent = 100(South Aspect x .5556)

West Percent = 100(West Aspect x .5556)

North Effect = Slope(%) x North Aspect(%)

East Effect = Slope(%) x East Aspect(%)

South Effect = Slope(%) x South Aspect(%)

West Effect = Slope(%) x West Aspect(%)

North aspect, east aspect, south aspect and **west aspect** are **aspect**, in degrees, rotated for each of the four compass points. As **aspect** is a circular variable (0 and 360 are equal), this was a means of linearizing the data.

A principal components analysis (Appendix C3) was performed on these variables to determine if multicollinearity existed and to derive the principal variables. The data distributions of the selected variables were examined by frequency analysis (Appendix C1). Inverse, square root and logarithm base 10 transformations (Appendix C1) were performed, where appropriate, to fit the variables to a normal distribution.

3.6.2 Meso Variables (Step 6b)

Meso variables reflect the relationship between the components of the canopy and factors relating to the description of the stand. The eight **tree species** were reworked into four tree forms with different crown structures, leaf forms and successional status (Hosie, 1973).

Form1 - Rounded crown, branch-free trunk, coniferous and evergreen, primary successional

= *Pinus contorta*

Form2 - Conical crown, branches to trunk base, coniferous and evergreen, secondary successional

= *Picea engelmannii x glauca* + *Picea mariana* + *Abies lasiocarpa*

Form3 - Conical crown, branches to trunk base, coniferous and deciduous, primary successional

= *Larix laricina*

Form4 - Rounded crown, branch-free trunk, decidous, primary successional

= *Populus tremuloides* + *Populus balsamifera* + *Betula papyrifera*

Tree Age (yrs)

Live Stems Form1(%) = 100 (Total Live Stems Form1 / Total Number of Stems)

Live Stems Form2(%) = 100 (Total Live Stems Form2 / Total Number of Stems)

Live Stems Form3(%) = 100 (Total Live Stems Form3 / Total Number of Stems)

Live Stems Form4(%) = 100 (Total Live Stems Form4 / Total Number of Stems)

Total Basal Area Form1(%) = 100 (Total Basal Area Form1 / Total Basal Area)

Total Basal Area Form2(%) = 100 (Total Basal Area Form2 / Total Basal Area)

Total Basal Area Form3(%) = 100 (Total Basal Area Form3

/ Total Basal Area)

Total Basal Area Form4(%) = 100 (Total Basal Area Form4 / Total Basal Area)

Dead Stems(%) = 100 (Dead Stems / Total Number of Stems)

A principal components analysis (Appendix C3) was performed on these variables to determine if multicollinearity existed and to derive the principal variables. The data distributions of the selected variables were examined by frequency analysis (Appendix C1). Inverse, square root and logarithm base 10 transformations (Appendix C1) were performed, where appropriate, to fit the variables to a normal distribution.

3.6.3 Micro Variables (Step 6c)

Micro variables consisted of those variables affecting substrate conditions. Substrate conditions affected germination and stand establishment as well as stand development.

Ecological moisture regime, **ecological nutrient regime** and **drainage** were collected as interval data. **Surface substrate** was available as numeric data within the categories of **bare rock**, **exposed soil**, **surface stones**, **dead wood**, **organic material** and **open water**. **Vegetation layers** were collected as numeric data within the categories of **tree**, **shrub**, **forb**, **graminoid**, **moss** and **lichen**. **Soil texture** was collected as categorical data and converted to interval data (fine, medium, coarse) utilizing the textural triangle (Agriculture Canada, 1987). **Soil texture**, **soil drainage**, **ecological moisture regime** and **ecological nutrient regime** consisted of interval data; these are numeric but discrete data. They were analyzed as continuous data.

Ecological Moisture Regime

Ecological Nutrient Regime

Bare Rock

Exposed Soil

Surface Stones

Dead Wood

Organic Material

Open Water

Tree

Shrub

Forb

Graminoid

Moss

Lichen

Soil pH

Soil Texture

Coarse Fragments

Solum Thickness

Organic Layer Thickness

Soil Drainage

A principal components analysis (Appendix C3) was performed on these variables to determine if multicollinearity existed and to derive the principal variables. The data distributions of the selected variables were examined by frequency analysis (Appendix C1). Inverse, square root and logarithm base 10 transformations (Appendix C1) were performed, where appropriate, to fit the variables to a normal distribution.

3.6.4 Categorical Variables (Step 6d)

The categorical variables belonged to classification systems that did not accommodate a numeric conversion. The categories were not interval and could not be analyzed as continuous variables. **Plant associations** were initially stratified by **ecoregion** as well as by plant community. **Ecoregion** was removed as part of the designation for **plant association** and **plant associations** that were similar across **ecoregions** were grouped. This was to avoid correlation and to reduce the number of **plant associations**. The resulting **plant association** categories are detailed in Appendix A. **Soil classification** was utilized only to the level of soil great group; soil subgroup would produce very low expected cell frequencies in cross-tabulation due to the large number of categories.

Ecoregion (9 categories)

Plant Association (16 categories)

Soil Classification (12 categories)

Cross-tabulations (Appendix C4) were performed to establish cell counts for the categories and to determine if there was interrelation between them. Categories were grouped, if possible, where cell counts were less than five or expected frequencies were less than one. Dummy variables were created for each of the final categories to accommodate these variables in the final analyses.

After the preliminary analyses were performed on these groups of variables, the final variables were compiled and a correlation matrix developed to eliminate highly correlated variables. A maximum allowable bivariate correlation of 0.700 (absolute value) was used as the criterion to eliminate some variables. Tabachnick and Fidell (1989 pg 87) suggested this limit to avoid multicollinearity and its associated problems when conducting a multiple

regression. This final data set of **site-conditions** variables was utilized in all further analyses.

3.6.5 **Stand-closure/Site-conditions** (Step 6e)

The data from the sample trees were analyzed to determine if there was a **stand-closure/site-conditions** relationship for the uncorrelated **stand closure** variables (Step 4). Multiple regressions were performed in a step-wise fashion (Appendix C4) on the **stand-closure** variables utilizing the final data set for the **site-conditions** variables. The multiple correlation coefficients for the **stand-closure/site-conditions** relationship were examined to determine if the correlations were significantly different from 0.000. The distributions of the residuals were examined and tested for autocorrelation (Appendix C4) to determine the validity of the results. The expected normal values for the residuals were plotted against their actual normal values and the graphs visually examined to determine how closely the points matched the standard straight line. The partial correlation coefficients (Appendix C4) for the **stand-closure/site-conditions** relationship by individual variables were also examined to determine if the correlations were significantly different from 0.000.

3.7 **Stem-form/Site-conditions** Relationship (Step 7)

If correlation coefficients (Appendix C4) with absolute values of 0.950 or greater were not achieved for the **stem-form/stand-closure** relationship (Step 5), an analysis of the **stem-form/site-conditions** relationship was undertaken. The establishment of a **stand-closure/site-conditions** relationship did not preclude the possibility of an independent **stem-form/site-conditions** relationship. There were many **site-conditions**; there may have been **site-**

conditions that affected **stem-form** but did not have any relationship to **stand-closure.**

The data from the sample trees were analyzed to determine if there was a **stem-form/site-conditions** relationship. Multiple regressions were performed in a step-wise fashion (Appendix C4) on **stem-form** utilizing the final data set for **site-conditions** variables. The multiple correlation coefficients for the **stem-form/site-conditions** relationship were examined to determine if the correlations were significantly different from 0.000. The distributions of the residuals were examined and tested for autocorrelation (Appendix C4) to determine the validity of the results. The expected normal values for the residuals were plotted against their actual normal values and the graphs were visually examined to determine how closely the points matched the standard straight line. The partial correlation coefficients (Appendix C4) for the **stem-form/site-conditions** relationship by individual variables were also examined to determine if the correlations were significantly different from 0.000.

If a significant **stand-closure/site-conditions** relationship and a significant **stem-form/site-conditions** relationship existed, a comprehensive regression analysis was undertaken utilizing the **stand-closure** variables as part of the **site-conditions** data set.

3.8 **Stem-form/Stand-closure/Site-conditions** (Step 8)

If correlation coefficients (Appendix C4) significantly different from 0.000 for the **stem-form/site-conditions** relationship (Step 7) and for the **stem-form/stand-closure** relationship (Step 5) were established, a comprehensive analysis was undertaken. Multiple regressions were performed in stepwise fashion (Appendix

C4) on the **stem-form** utilizing the final data set for the **site-conditions** variables and all of the **stand-closure** variables. The distributions of the residuals were examined and tested for autocorrelation (Appendix C4) to determine the validity of the results. The expected normal values for the residuals were plotted against their actual normal values and the graphs visually examined to determine how closely the points matched the standard straight line.

If any of the **stand-closure** variables were selected, a back check was performed; separate stepwise regressions (Appendix C4) were performed on the **stem-form** utilizing the final data set for the **site-conditions** variables and each of the **stand-closure** variables. The distribution of the residuals was examined and tested for autocorrelation (Appendix C4) to determine the validity of the results. The expected normal values for the residuals were plotted against their actual normal values and the graphs visually examined to determine how closely the points matched the standard straight line.

It is not within the scope of this study to establish that a relationship between any of the variables does not exist. It is only possible to establish that a significant relationship does exist. In examining the results of the analysis, it should be noted that the failure to establish a statistically significant relationship is potentially due to a number of factors:

1) The relationship may not exist. Stabilization against wind sway may have been achieved through other means than changes in **stem-form**. Alternatively, there may have been so much individual

variation in the response to **stand-closure** and wind sway that a relationship could not be established.

2) Inadequate sampling. It may be that the sample size was insufficient or that the distribution was too poor to statistically establish a relationship.

3) Inappropriate variables. It may be that a relationship existed but the variables chosen to represent the **stand-closure** or the **site-conditions** were not appropriate and did not adequately reflect the concepts being tested in the study.

4) Random factors. Under field conditions there was no control for random events; the variability introduced by the response to such events may have masked a relationship.

4. RESULTS

The detailed results for the eight analytical steps (Figure 7) are presented in the same order as the analysis section. Summaries of the **tree species** differences in **stem-form**, the correlation coefficients between the four **stand-closure** variables, the correlation coefficients for the **stem-form/stand-closure** relationship, the correlation coefficients for the **stand-closure/site-conditions** relationship, the correlation coefficients for the **stem-form/site-conditions** relationship and the correlation coefficients for the **stem-form/stand-closure/site-conditions** relationship appear as tables throughout this section.

4.1 **Stand-closure** Calculation (Step 1)

Data for the four variables representing **stand-closure**: **crown closure**, **total basal area**, **total volume** and **total number of stems**, were compiled for all sample trees. **Crown closure** was available from the raw environmental data; **total basal area**, **total volume** and **total number of stems** were calculated from the raw timber data. There were no sample trees with missing data for these four variables.

4.2 Species Separation (Step 2)

The data were separated into nine data sets; one set for each of the eight **tree species** present in the study area and one all-inclusive data set. The resulting data sets and the total number of samples present in each are as follows:

Pinus contorta - 279 samples

Picea mariana - 72 samples

Picea engelmannii x glauca - 123 samples

Abies lasiocarpa - 49 samples

Larix laricina - 9 samples

Populus tremuloides - 86 samples

Betula papyrifera - 12 samples

Populus balsamifera - 23 samples

All-species - 653 samples

4.3 **Stem-form** Calculation (Step 3)

The **stem-form** was calculated for each sample tree by dividing the diameter at breast height by total height. There were no missing data. The distributions for each species data set were tested for skewness and kurtosis (Appendix C1) and some were found to be significantly different from normal. Logarithmic (base 10) and square root transformations (Appendix C1) were performed on all of the nine species data sets. The logarithmic transformations resulted in the most consistent improvement. The data sets for *Pinus contorta*, *Populus tremuloides* and all species displayed significant (alpha=0.050) deviation from a normal distribution after transformation. As these data sets were large (n=279, n=86, n=653 respectively) and the visual appearance of the distributions approximated normal, further analysis was undertaken (Tabachnick and Fidell, 1989 pg 73-74; Kleinbaum and Kupper, 1978 pg 16).

Bartlett's-Box F test (Appendix C2) was performed on the **stem-form** data to determine if there was homogeneity in the variances for the species data sets. The results indicated that there was no significant difference in variance. The analysis of variance (Appendix C2) of the **stem-form** by **tree species** indicated that there was significant difference in the **stem-form** between some species data sets (Table 2). The separation of the data by **tree species** produced unequal sample sizes; range tests were not applied to

determine which species means were significantly different. The application of range tests would have required the production of harmonic means and would have resulted in a possible loss of information. The examination of the means does suggest that the **stem-form** data for *Picea engelmannii x glauca* was different from all other species; on average, more taper was exhibited by this species. Less taper was exhibited by *Larix laricina*, *Populus tremuloides*, *Betula papyrifera* and *Populus balsamifera*. As some data sets exhibited significant skew and/or kurtosis (Appendix C1) even after transformation, the Kruskal-Wallis nonparametric test for significant difference (Appendix C2) was also performed to verify that species differences did exist.

4.4 **Stand-closure** Variables Elimination (Step 4)

The data distributions of the nine species data sets for the four variables representing **stand-closure** were examined for skewness and kurtosis (Appendix C1). **Crown closure** displayed significant (alpha=0.050) kurtosis (Appendix C1) for *Picea mariana* and the all species data sets. As these data sets are large (n=72, n=653 respectively) and the visual appearance of the distribution approximated normal, further analysis was undertaken (Tabachnick and Fidell, 1989 pg 74-74; Kleinbaum and Kupper, 1978 pg 16). Although transformation may have improved these individual species data sets, it would have produced deviation in the other species data sets.

Table 2

PARAMETRIC AND NONPARAMETRIC TESTS
FOR SIGNIFICANT GROUP DIFFERENCES
STEM–FORM BY SPECIES
LOG base 10 STEM–FORM (STFORMLG)
MEAN (u)
STANDARD DEVIATION (s)
MEAN RANK (r)

	ANALYSIS OF VARIANCE		KRUSKAL–WALLIS	
	STFORMLG	STFORMLG	STFORMLG	
SPECIES	MEAN cm/m u=	STANDARD DEVIATION s=	MEAN RANK r=	N
Pinus contorta	0.103 a d'	0.098	324.05	279
Picea mariana	0.104 c d'	0.102	328.63	72
Picea engelmannii 'x' glauca	0.141 d	0.106	396.77	123
Abies lasiocarpa	0.104 b d'	0.094	331.07	49
Larix laricina	0.062 d'	0.078	240.17	9
Populus tremuloides	0.064 a'b'c'd'	0.114	276.54	86
Betula papyrifera	0.033 a'd'	0.104	218.33	12
Populus balsamifera	0.069 d'	0.068	255.28	23
All–species	0.102	0.104		653

'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations

a a' denotes pairs of species that are significantly different at alpha=0.050

Logarithmic (base 10) and square root transformations (Appendix C1) were performed on **total number of stems**. The logarithmic transformation produced the most consistent improvement in distribution. The data sets for *Pinus contorta*, *Picea mariana*, *Populus tremuloides*, *Populus balsamifera* and all species displayed significant (alpha=0.050) deviation from a normal distribution even after transformation. Apart from *Populus balsamifera*, these data sets were large (n=279, n=72, n=86, n=23, n=653 respectively) and the distributions visually approximated normal. The results from *Populus balsamifera* should be regarded with caution; poor distribution and small sample size may weaken further analysis. For the other data sets, further analysis was undertaken unconditionally (Tabachnick and Fidell, 1989 pg 73-74; Kleinbaum and Kupper, 1978 pg 16). All further analysis involving **total number of stems** was performed on the logarithmic transformation.

Total basal area displayed significant (alpha=0.050) skewness and kurtosis (Appendix C1) for *Abies lasiocarpa*. As this was a large data set (n=49) and the visual appearance approximated normal, further analysis was undertaken (Tabachnick and Fidell, 1989 pg 73-74; Kleinbaum and Kupper, 1978 pg 16). Although transformation may have improved this data set, it would have produced deviation in the other data sets.

Logarithmic (base 10) and square root transformations (Appendix C1) were performed on **total volume**. A square root transformation produced the most improvement in distribution for **total volume**. The data sets for *Picea mariana* and *Picea engelmannii x glauca* displayed deviation from a normal distribution after transformation. As these data sets were large (n=72, n=123

respectively) and the visual appearance of the distribution approximated normal, further analysis was undertaken (Tabachnick and Fidell, 1989 pg 73-74; Kleinbaum and Kupper, 1978 pg 16). All further analysis involving **total volume** was performed on the square root transformation.

The correlation coefficients (Appendix C4) between the four **stand-closure** variables, **crown closure**, **total basal area**, **total volume** and **total number of stems**, are given in Table 3. The absolute values of the correlation coefficients were tested for high correlation; a significance level greater than 0.950 was considered a high correlation. The correlation coefficients were also tested for significant difference from 0.000.

The results indicated that for *Larix laricina*, **crown closure** was highly correlated with **total basal area**, **total stem volume** and **total number of stems**. On this basis, **crown closure** was eliminated from the analysis. **Total basal area** and **total volume** were highly correlated for *Picea mariana*, *Larix laricina*, *Populus tremuloides* and *Betula papyrifera*. **Total volume** was eliminated from further analysis. **Total basal area** was selected in preference to **total volume** as **total volume** contains a height component. **Stem-form** and **total volume** contain both a diameter and a height component which may potentially complicate the analysis. The role of height as an indicator of **stand-closure** is not as clear as the role of diameter as a component of basal area.

4.5 **Stem-form/Stand-closure** Relationship (Step 5)

Table 3

CORRELATION COEFFICIENTS
STAND–CLOSURE
CROWN CLOSURE (TREE)
LOG base 10 TOTAL NUMBER OF STEMS (TNSLOG)
TOTAL BASAL AREA (TBA)
SQUARE ROOT TOTAL VOLUME (TVOLSR)
CORRELATION COEFFICIENT (r)

SPECIES	TREE TNSLOG r =	TREE TBA r =	TREE TVOLSR r =	TNSLOG TBA r =	TNSLOG TVOLSR r =	TBA TVOLSR r =	N
Pinus contorta	0.408	0.431	0.363	0.290	−0.034+	0.904	279
Picea mariana	0.582	0.785	0.735	0.605	0.351	0.940*	72
Picea engelmannii 'x' glauca	0.401	0.433	0.274	0.261	−0.091+	0.879	123
Abies lasiocarpa	0.246+	0.185+	0.222+	0.173+	−0.208+	0.884	49
Larix laricina	0.880*	0.874*	0.892*	0.776	0.726+	0.974*	9
Populus tremuloides	0.734	0.437	0.296	0.288	0.061+	0.937*	86
Betula papyrifera	0.843	0.280+	0.179+	0.090+	0.039+	0.979*	12
Populus balsamifera	0.692	0.408+	−0.005+	0.277+	−0.219+	0.844	23
All–species	0.416	0.498	0.399	0.228	−0.102	0.906	653

* |r| is not significantly less than 0.950 (alpha=.05)
+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations

The analysis of the **stem-form/stand-closure** relationship included two **stand-closure** variables. The relationship between the **stem-form** and the **total basal area** was examined independently of the relationship between the **stem-form** and the **total number of stems**. The results of these two sets of analyses are given in Table 4. The table includes the presence of high correlation (0.950) and significant difference from 0.000.

The correlation coefficients (Appendix C4) for the **stem-form** and the **total basal area** indicated that there was a significant relationship for some species. For five of the species data sets the correlation coefficient was significantly different from 0.000.The relationship was not a strong one; all correlation coefficients were significantly less than 0.950. For the evergreen species, *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca* and *Abies lasiocarpa*, and all species, the **total basal area** was a partial predictor of **stem-form**. For the deciduous species, *Larix laricina*, *Populus tremuloides*, *Betula papyrifera* and *Populus balsamifera*, the **total basal area** was not a predictor of the **stem-form**.

The correlation coefficients (Appendix C4) for the **stem-form** and the **total number of stems** indicated that there was a significant relationship for most species. In six of the species data sets the correlation coefficient was significantly different from 0.000. This relationship was also not a strong one; all correlation coefficients were significantly less than 0.950. For *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca*, *Populus tremuloides* and *Populus balsamifera*, and all species, the **total**

Table 4

CORRELATION COEFFICIENTS
STAND–CLOSURE and STEM–FORM
LOG base 10 TOTAL NUMBER OF STEMS (TNSLOG)
TOTAL BASAL AREA (TBA)
LOG base 10 STEM FORM (STFORMLG)
CORRELATION COEFFICIENT (r)

SPECIES	STFORMLG TBA r =	STFORMLG TNSLOG r =	N
Pinus contorta	−0.306	−0.346	279
Picea mariana	−0.470	−0.552	72
Picea engelmannii 'x' glauca	−0.369	−0.341	123
Abies lasiocarpa	−0.364	−0.269+	49
Larix laricina	0.238+	0.431+	9
Populus tremuloides	−0.107+	−0.536	86
Betula papyrifera	−0.002+	−0.616+	12
Populus balsamifera	−0.049+	−0.551	23
All–species	−0.242	−0.380	653

* |r| is not significantly less than 0.950 (alpha=.05)
+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations

number of stems was a partial predictor of the **stem-form.** For *Abies lasiocarpa*, *Larix laricina*, and *Betula papyrifera*, the **total number of stems** was not a predictor of the **stem-form.** All correlation coefficients were significantly less than 0.950; the **stem-form/stand-closure** relationship was not a strong one and further analysis was undertaken.

4.6 **Stand-closure/Site-conditions** Relationship (Step 6)

The **site-conditions** variables were separated into macro, meso, micro and categorical variables for initial screening. Preliminary analysis on the **site-conditions** variables reduced the number of variables from 77 to 48. Transformations (Appendix C1) were performed on the remaining variables where appropriate. The categorical variables were integrated into a comprehensive data set using dummy variables, resulting in a reduction in the number of variables to 45. The **site-conditions** variables were further reduced to 42 by elimination of one of each pair of highly correlated **site-conditions** variables.

4.6.1 **Site-conditions** (Steps 6a-d)

The principal components analyses (Appendix C3) and frequency analyses (Appendix C1) on the macro, meso and micro variables resulted in a data set of 18 variables.

Elevation

North Effect

East Effect

South Effect

West Effect

Tree Age

Live Stems Form1

Live Stems Form2

Live Stems Form3

Live Stems Form4

Dead Stems

Exposed Mineral

Dead Wood

Open Water

Soil pH

Soil Texture

Solum Thickness

Soil Drainage

The values for **bare rock, exposed soil** and **surface stones** were summed into the single category of **exposed mineral.** The data distributions for all variables were examined and transformations (Appendix C1) were performed on **north effect, east effect, south effect** and **west effect, live stems form1, live stems form2, live stems form3, live stems form4, tree age, dead stems, dead wood, soil pH** and **solum thickness.** Logarithmic (base 10) and inverse transformations were performed on **north effect, east effect, south effect, west effect** and **dead wood.** Logarithmically transformed variables were not consistently better in distribution; both untransformed and transformed variables were included in further analysis.

Square root and logarithmic (base 10) transformations (Appendix C1) were performed on **live stems form1, live stems form2, live stems form3, live stems form4** and **solum thickness.** The square root transformations did not produce consistently better distribu-

tions; both untransformed and transformed variables were included in further analysis.

Square root transformations (Appendix C1) were performed on **tree age** and **soil pH** with consistent improvement in distribution; only the transformed variables were included in further analysis.

The data distributions for **exposed mineral** and **open water** were too poor to be improved by transformation. These variables were converted to categorical variables and assigned dummy values (1=present;0=absent). They were then included with the cross-tabulations (Appendix C4) performed on the categorical variables.

The preliminary analysis performed on the categorical variables reduced the number of categories from 37 to 30. The results of the cross-tabulations (Appendix C4) between categories indicated that **soil great group** contained many categories with low expected cell frequencies (Appendix C1). A reduction in the number of categories by grouping the **soil great group** data into **soil order** produced better results.

Ecoregion (9 categories)

Plant Association (16 categories)

Soil Order (5 categories)

The conversion of the categorical data to one variable per category (dummy variables) resulted in a reduction of the number of **ecoregions** from nine to six. Three of the **ecoregion** designations were transitional; the site was classified as having characteristics of two **ecoregions**. The numeric conversion of these transitional **ecoregions** involved placing value in each of the two basic **ecoregions**, thus eliminating the transitional categories. The reduced number of variables was then compiled into a comprehensive

site-conditions variables data set. A correlation analysis (Appendix C4) of all of the **site-conditions** variables indicated that one of the **plant associations**, *Salix/Carex/Sphagnum*, was highly correlated with **live stems form3**. **North effect** and **east effect** were highly correlated with **south effect** and **west effect** respectively. *Salix/Carex/Sphagnum*, **north effect** and **east effect** were eliminated from further analysis.

4.6.2 **Stand-closure/Site-conditions** (Step 6e)

The **stand-closure/site-conditions** relationship was analyzed using the final set of **site-conditions** variables. Two independent analyses were performed utilizing the two **stand-closure** variables, the **total basal area** and the **total number of stems**. Each of the nine species data sets was analyzed in a step-wise regression (Appendix C4) utilizing the **site-conditions** variables and each of the pair of untransformed/transformed variables; in total, seven separate regressions were performed on each of the species data sets for each **stand-closure** variable. The multiple correlation coefficients (Appendix C4) were assessed for improvement for the following:

1) all variables untransformed
2) all variables transformed
3) **south effect** and **west effect** transformed
4) **tree age** transformed
5) **live stems form1-4** and **dead stems** transformed
6) **dead wood** transformed
7) **solum thickness** transformed

The best fit to a multiple regression was achieved with untransformed **south effect** and **west effect**, square root **live stems**

forms1-4 and **dead stems**, square root **tree age**, untransformed **dead wood** and untransformed **solum thickness**. The resulting multiple correlation coefficients are presented in Table 5.

The examination of the distributions of the residuals and the plots of observed versus expected standardized residuals gave the following results. The distributions approximated normal and the plots approximated straight lines for the *Pinus contorta* and all species data sets. The distributions were poorer and the plots less linear for the *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa* and *Populus tremuloides* data sets. The distributions were very poor and the plots deviated substantially from linear for the *Larix laricina*, *Betula papyrifera* and *Populus balsamifera* data sets. This follows a trend of decreasing sample size and was valid for the relationship of the **site-conditions** variables with both the **total basal area** and the **total number of stems**.

Tests performed on the residuals for positive autocorrelation (Appendix C4) were either inconclusive or indicated that positive autocorrelation was present for the **stand-closure/site-conditions** relationship for both **stand closure** variables with the following exceptions; positive autocorrelation was not present for the *Betula papyrifera* data set for **total basal area** with the **site-conditions** variables; positive autocorrelation was not present for the *Abies lasiocarpa* and *Populus balsamifera* data sets for **total number of**

Table 5

MULTIPLE CORRELATION COEFFICIENTS
STAND–CLOSURE and SITE–CONDITIONS
TOTAL BASAL AREA (TBA)
LOG base 10 TOTAL NUMBER STEMS (TNSLOG)
SITE–CONDITIONS (42 VARIABLES)
CORRELATION COEFFICIENT (r)

SPECIES	TBA SITE CONDITIONS r =	TNSLOG SITE CONDITIONS r =	N#
Pinus contorta	0.742	0.675	274
Picea mariana	0.770	0.571	59
Picea engelmannii 'x' glauca	0.758	0.767	117
Abies lasiocarpa	0.845	0.820	47
Larix laricina	0.970	1.000 F undefined	5
Populus tremuloides	0.777	0.776	83
Betula papyrifera	0.996	1.000 F undefined	12
Populus balsamifera	>0.999	0.981	23
All–species	0.741	0.609	624

\+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
minimum number of cases, actual number of cases varies depending on which site variables are involved

stems with the **site-conditions** variables.

The correlation coefficients (Appendix C4) for both of the **stand-closure** variables were of similar magnitude and direction. For *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa*, *Populus tremuloides* and the all-species data set, the **site-conditions** were partial predictors of both **total basal area** and **total number of stems** (multiple correlation coefficients in the range of 0.571 to 0.845). For *Larix laricina*, *Betula papyrifera* and *Populus balsamifera*, the **site-conditions** were predictors of both **total basal area** and **total number of stems** (multiple correlation coefficients in the range of 0.970 to 1.000).

A full description of the **stand-closure/site-conditions** relationship was detailed as partial correlation coefficients (Appendix C4) for each of the **site-conditions** variables in the final regression. A t-test (Appendix C4) was utilized to determine if each partial correlation coefficient was significantly different from 0.000. These partial correlation coefficients for **total basal area** and its associated **site-conditions** variables and for **total number of stems** and its associated **site-conditions** variables are listed in Appendix B.

4.7 **Stem-form/Site-conditions** Relationship (Step 7)

The **stem-form/site-conditions** relationship was analyzed using the reduced, compiled set of **site-conditions** variables. Two independent analyses were performed; one on the **stem-form/site-conditions** relationship alone and the other on the **stem-form/stand-closure/site-conditions** relationship. Each of the nine species data sets were analyzed in a step-wise regression (Appendix C4) utilizing the **site-conditions** variables and each of the pair of

untransformed/transformed variables; in total, seven separate regressions were performed on each of the species data sets for each of the two **stem-form** analyses. The multiple correlation coefficients (Appendix C4) were assessed for improvement for the following:

1) all variables untransformed
2) all variables transformed
3) **south effect** and **west effect** transformed
4) **tree age** transformed
5) **live stems form1-4** and **dead stems** transformed
6) **dead wood** transformed
7) **solum thickness** transformed

The best fit to a multiple regression was achieved with untransformed **south effect** and **west effect**, square root **live stems forms1-4** and **dead stems**, square root **tree age**, untransformed **dead wood** and untransformed **solum thickness**. The resulting multiple correlation coefficients are presented in Table 6.

The examination of the distributions of the residuals and the plots of observed versus expected standardized residuals gave the following results. The distributions approximated normal and the plots approximated straight lines for the *Pinus contorta* and all species data sets. The distributions were slightly poorer and the plots somewhat less linear for the *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa* and *Populus tremuloides* data sets. The distributions were poor and the plots less linear for the *Betula papyrifera* and *Populus balsamifera* data sets. As with the **stand**

Table 6

MULTIPLE CORRELATION COEFFICIENTS
STEM–FORM and SITE–CONDITIONS
plus/minus STAND–CLOSURE
TOTAL BASAL AREA (TBA)
LOG base 10 TOTAL NUMBER STEMS (TNSLOG)
LOG base10 STEM–FORM (STFORMLG)
SITE–CONDITIONS (42 VARIABLES)
CORRELATION COEFFICIENT (r)

SPECIES	STFORMLG SITE CONDITIONS r =	STFORMLG TBA TNSLOG SITE CONDITIONS r =	N#
Pinus contorta	0.673	0.715	274
Picea mariana	0.653	0.673	59
Picea engelmannii 'x' glauca	0.712	0.683	117
Abies lasiocarpa	0.468	0.624	47
Larix laricina	0.000 no variables	0.000 no variables	5
Populus tremuloides	0.498	0.764	83
Betula papyrifera	0.632	0.632	12
Populus balsamifera	0.706	0.706	23
All–species	0.560	0.650	624

\+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
minimum number of cases, actual number of cases varies depending on which site variables are involved

-closure/site-conditions relationship, this follows a trend of decreasing sample size. There were no variables for *Larix laricina*, consequently there were no residuals to examine.

Tests performed on the residuals for positive autocorrelation (Appendix C4) were inconclusive (two data sets) or indicated that positive autocorrelation was not present for the **stem-form/site-conditions** relationship. There was one exception, positive autocorrelation was present for the *Populus tremuloides* data set.

The multiple correlation coefficients (Appendix C4) for the **stem-form/site-conditions** relationship were generally lower in value than the correlation coefficients for the **stem-form/stand-closure/site-conditions** relationship. For *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa*, *Populus tremuloides*, *Betula papyrifera*, *Populus balsamifera* and the all-species data set, **site-conditions** were partial predictors of **stem-form** (multiple correlation coefficients were positive and in the range of 0.468 to 0.712). **Site-conditions** were not predictors of **stem-form** for *Larix laricina*.

A full description of the **stem-form/site-conditions+/-stand-closure** relationship was detailed as partial correlation coefficients (Appendix C4) for each of the **site-conditions** variables in the final regressions. A t-test (Appendix C4) was utilized to determine if each partial correlation coefficient was significantly different from 0.000. These partial correlation coefficients are listed in Appendix B.

4.8 **Stem-form/Stand-closure/Site-conditions** Relationship(Step8)

The inclusion of both of the two **stand-closure** variables, **total basal area** and **total number of stems**, with the **site-conditions**

variables in the regression with **stem-form** improved the multiple correlation coefficients (Appendix C4) for seven of the species data sets. Table 6 contains the values for the **stem-form/site-conditions** relationship and **stem-form/stand-closure/site-conditions** relationship. *Larix laricina* displayed no significant relationship and *Picea engelannii x glauca* displayed a small drop (0.029). For *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa*, *Populus tremuloides*, *Betula papyrifera*, *Populus balsamifera* and the all-species data set, **site-conditions** plus **stand-closure** were partial predictors of **stem-form** (multiple correlation coefficients ranged from 0.624 to 0.764). For *Larix laricina*, **site-conditions** plus **stand-closure** were not predictors of **stem-form**.

The examination of the distributions of the residuals and the plots of observed versus expected standardized residuals gave the following results. The distributions approximated normal and the plots approximated straight lines for the *Pinus contorta* and all species data sets. The distributions were slightly poorer and the plots somewhat less linear for the *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa* and *Populus tremuloides* data sets. The distributions were poor and the plots less linear for the *Betula papyrifera* and *Populus balsamifera* data sets. As with the **stem-form/site-conditions** relationship and the **stand-closure/site-conditions** relationship, this follows a trend of decreasing sample size. There were no variables for *Larix laricina*, consequently there were no residuals to examine.

Tests performed on the residuals for positive autocorrelation (Appendix C4) were either inconclusive (two data sets) or indicated

that positive autocorrelation was not present for the **stem-form/site-conditions** relationship or the **stem-form/stand-closure-/site-conditions** relationship.

The stepwise regression analyses (Appendix C4) were then conducted using each of two **stand-closure** variables separately. The multiple correlation coefficients (Appendix C4) are presented in Table 7.

The examination of the distributions of the residuals and the plots of observed versus expected standardized residuals gave the following results. The distributions approximated normal and the plots approximated straight lines for the *Pinus contorta* and all species data sets. The distributions were slightly poorer and the plots somewhat less linear for the *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa* and *Populus tremuloides* data sets. The distributions were poor and the plots less linear for the *Betula papyrifera* and *Populus balsamifera* data sets. This was valid for both **stand-closure** variables. As with the **stem-form/site-conditions** relationship and the **stand-closure/site-conditions** relationship, this follows a trend of decreasing sample size. There were no variables for *Larix laricina*, consequently there were no residuals to examine.

Tests performed on the residuals for positive autocorrelation (Appendix C4) were either inconclusive (two data sets) or indicated that positive autocorrelation was not present for the **stem-form/stand-closure (total basal area)/site-conditions** relationship. There was one exception, the *Populus tremuloides* data set displayed positive autocorrelation.

Table 7

MULTIPLE CORRELATION COEFFICIENTS
STEM–FORM and SITE–CONDITIONS
plus STAND–CLOSURE
TOTAL BASAL AREA (TBA)
LOG base 10 TOTAL NUMBER STEMS (TNSLOG)
LOG base10 STEM–FORM (STFORMLG)
SITE–CONDITIONS (42 VARIABLES)
CORRELATION COEFFICIENT (r)

SPECIES	STFORMLG SITE CONDITIONS & TBA r =	STFORMLG SITE CONDITIONS & TNSLOG r =	N#
Pinus contorta	0.668*	0.720*	274
Picea mariana	0.694*	0.673*	59
Picea engelmannii 'x' glauca	0.712	0.683*	117
Abies lasiocarpa	0.468	0.624*	47
Larix laricina	0.000 no variables	0.000 no variables	5
Populus tremuloides	0.498	0.764*	83
Betula papyrifera	0.632	0.632	12
Populus balsamifera	0.706	0.706	23
All–species	0.601*	0.650*	624

* stand closure was part of regression
+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
minimum number of cases, actual number of cases varies depending on which site variables are involved

Tests performed on the residuals for autocorrelation (Appendix C4) were either inconclusive (two data sets) or indicated that positive autocorrelation was not present for the **stem-form/stand-closure (total number of stems)/site-conditions** relationship.

The *Pinus contorta* and all-species data sets consistently displayed inconclusive results for positive autocorrelation in the regression of **stem-form** with any variation of **site-conditions** variables.

The inter-relationship of the **site-conditions** variables and the **stand-closure** variables within the regression with **stem-form** was calculated as the difference between the absolute value of the bivariate correlation coefficient (Appendix C4) for the **stem-form/stand-closure** relationship and the semi-partial correlation coefficient (Appendix C4) for **stand-closure** within the **stem-form/stand-closure/site-conditions** relationship. The correlation coefficients, semi-partial correlation coefficients and inter-relationship for the two **stand-closure** variables are presented in Tables 8 and 9.

For the **total basal area**, the inter-relationship values vary from 0.002 to 0.364. For *Picea engelmannii x glauca*, *Abies lasiocarpa*, *Larix laricina*, *Populus tremuloides*, *Betula papyrifera* and *Populus balsamifera*, the **total basal area** was not included in the final regressions for the **stem-form/stand-closure/site-conditions** relationship.

For the **total number of stems**, the inter-relationship values vary from -0.144 to 0.661. For *Larix laricina*, *Betula papyrifera* and *Populus balsamifera*, there was high inter-relationship; the **total number of stems** was not included in the final regressions for

Table 8

INTER–RELATIONSHIP
STEM–FORM, STAND–CLOSURE (TBA),
SITE–CONDITIONS
TOTAL BASAL AREA (TBA)
LOG base10 STEM–FORM (STFORMLG)
SITE–CONDITIONS
BIVARIATE CORRELATION COEFFICIENT (r)
SEMI–PARTIAL CORRELATION COEFFICIENT (s)
INTER–RELATIONSHIP (i)

SPECIES	STFORMLG TBA r =	STFORMLG SITE CONDITIONS plus TBA@ s =	INTER–RELATIONSHIP SITE CONDITIONS & TBA i=|r|–|s|$
Pinus contorta	−0.306	−0.270	0.036
Picea mariana	−0.470	−0.403	0.067
Picea engelmannii 'x' glauca	−0.369	0.000	0.369
Abies lasiocarpa	−0.364	0.000	0.364
Larix laricina	0.238+	0.000	0.238
Populus tremuloides	−0.107+	0.000	0.107
Betula papyrifera	−0.002+	0.000	0.002
Populus balsamifera	−0.049+	0.000	0.049
All–species	−0.242	−0.231	0.011

\+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
@ TBA within STEM–FORM/SITE–CONDITIONS+ STAND–CLOSURE
$ adapted from Tabachnick and Fidell (1989)

Table 9

INTER–RELATIONSHIP
STEM–FORM, STAND–CLOSURE (TNS), SITE–CONDITIONS
LOG base10 TOTAL NUMBER STEMS (TNSLOG)
LOG base10 STEM–FORM (STFORMLG)
SITE–CONDITIONS
BIVARIATE CORRELATION COEFFICIENT (r)
SEMI–PARTIAL CORRELATION COEFFICIENT (s)
INTER–RELATIONSHIP (i)

SPECIES	STFORMLG TNSLOG r =	STFORMLG SITE CONDITIONS plus TNSLOG@ s =	INTER–RELATIONSHIP SITE CONDITIONS TNSLOG i=|r|–|s|$
Pinus contorta	−0.346	−0.319	0.027
Picea mariana	−0.552	−0.497	0.055
Picea engelmannii 'x' glauca	−0.341	−0.264	0.077
Abies lasiocarpa	−0.269+	−0.413	−0.144
Larix laricina	0.431+	0.000	0.431
Populus tremuloides	−0.536	−0.544	−0.008
Betula papyrifera	−0.616+	0.000	0.616
Populus balsamifera	−0.551	0.000	0.551
All–species	−0.380	−0.381	−0.001

+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
@ TNS within STEM–FORM/SITE–CONDITIONS + STAND–CLOSURE
$ adapted from Tabachnick and Fidell (1989)

the **stem-form/stand-closure/site-conditions** relationship. For the other six species data sets, there was little inter-relation.

4.9 Summary of Results

In summary, there was a statistically significant **stem-form/stand-closure** relationship, a statistically significant **stand-closure/site-conditions** relationship and a statistically significant **stem-form/site-conditions** relationship for some species.

4.9.1 **Stem-form/Stand-closure**

The **stem-form/stand-closure** relationship was negative but not strong for all species except *Larix laricina;* an increase in the **stand-closure** produced a decrease in the taper. **Stand-closure** can be broken down into the **total basal area** and the **total number of stems**. Both **total basal area** and **total number of stems** were partial predictors of **stem-form**, but **total number of stems** had a stronger relationship with the **stem-form.**

4.9.2 **Stand-closure/Site-conditions**

The **stand-closure/site-conditions** relationship was positive, as these were multiple correlation coefficients, and moderately strong. There was no consistent difference in the strength of the relationship of the **total basal area** with the **site-conditions** versus the relationship of the **total number of stems** with the **site-conditions.**

4.9.3 **Stem-form/Site-conditions**

The **stem-form/site-conditions** relationship was positive, as these were multiple correlation coefficients, and fairly strong. The exception was *Larix laricina*, which had no **stem-form/site-conditions** relationship. For most species, **site-conditions** were partial predictors of **stem-form.**

4.9.4 **Stem-form/Stand-closure/Site-conditions**

The **stem-form/stand-closure/site-conditions** relationship was positive, as these were multiple correlation coefficients, and stronger than the **stem-form/site-conditions** relationship. The exception was *Larix laricina*, which had no **stem-form/site-conditions** relationship with or without the **stand-closure** variables. Of the two **stand-closure** variables, the **total number of stems** was a more independent predictor of the **stem-form** than the **total basal area.** The correlation coefficients suggest that the variables utilized were a greater influence on **stem-form** and **stand-closure** than stochastic/unmeasured factors (r values were greater than 0.050).

5. DISCUSSION

In resolving any scientific question that involves the use of statistical methods, it is imperative that the statistical result be incorporated within scientific logic. The statistical methods employed may verify or refute a relationship but the results must be taken within the context of a scientific explanation. The statistical result of the **stem-form/stand-closure/site-conditions** relationships only has biological value if it is logical and explainable.

The results of an extended analysis such as this cannot be examined independently of the sampling methodology and the statistical tools utilized to arrive at the results. The samples that are utilized should truly represent the population, the statistical tools should be appropriate for the hypothesis and it should be possible to place these results within a broader context. The failure to establish a statistically significant relationship even if there is a sound biological basis may be due to a number of factors:

1) The relationship, although logical, may not exist.

2) The sampling may be inadequate, leading to inadequate representation.

3) The variables may be inappropriate and may not represent the relationship.

4) Random factors may obscure the relationship.

The discussion of the **stem-form/stand-closure/site-conditions** relationship as part of tree adaptation to wind force entails the examination of significant results with consideration given to the four alternatives for non-significant results. The implications of

the data collection in terms of sampling, the analysis in terms of statistical design, the results in terms of relationships and the limitations and extrapolations of the study are examined with respect to biological explanation and statistical results.

5.1 Sampling

Although data collection was not part of this thesis, the adequacy of the sampling has implications in discussing the biological relationships. Random sampling is perhaps the first principle in any statistical analysis; this was not undertaken by the agencies responsible for data collection. Instead, selective sampling was required to cover the range in **tree species**, **stem-form**, **stand-closure** and **site-conditions** over the entire area and within a reasonable time frame. If completely stratified selective sampling had been followed, without any consideration for geographic representation, the **tree species** distributions would have been even and non-representative of the populations being analyzed.

The population distributions were biased toward *Pinus contorta*, lower **stem-form** (less taper), denser **stand-closure** (larger **total number of stems)**, and a **tree age** of approximately 80 to 90 years. This was consistent with the stand history and species composition of other areas, particularly the Kananaskis area to the south where the fire cycle between 1730 and 1980 was deemed to be 90 years (Johnson and Larsen, 1991). Aerial photography indicated that there were large expanses of *Pinus contorta* of similar age, which would have likely regenerated after a major fire occurred through this area in the 1870-1880 time period.

The implications of random sampling were discussed by Verbyla and Fisher (1989) with reference to the relationship between soils and

site index. It was concluded that rarer **site-conditions** (those with a high site index in this case) would be undersampled and a deliberate attempt should be made to sample a wide range of sites.

5.1.1 Tree Species

As the data were stratified by **tree species** with no prior knowledge of species counts, it was anticipated that the number of samples was not adequate to yield significant results for some **tree species;** relationships could not be established for *Larix laricina* (nine samples) and *Betula papyrifera* (12 samples).

Tabachnick and Fidell (1989 pg 71) suggest a minimum of 20 degrees of freedom to qualify as a large population. While *Populus balsamifera* was represented by 23 samples, it should be considered that there were usually two and occasionally three sample trees from each **tree species** at each site. There were in fact only 16 sites for *Populus balsamifera;* this is insufficient to qualify as a large population. It was not appropriate to average the data for the trees present at each site. Although the **stand-closure** and **site-conditions** were consistent at each site, each sample tree represented a unique combination for the **stem-form** and **tree age.** A minumum of at least 40 samples from 20 sites would qualify as a large population.

For *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa*, *Populus tremuloides* and the all-species data sets, the number of samples and range of the **site-conditions** was more than adequate to satisfy the requirements in terms of population size and the range in the **site-conditions.**

5.1.2 **Stem-form**

The distributions for the **stem-form** data were not normal; transformation produced a better fit to a standard normal distribution for most **tree species**. The positive skew of the data accurately reflects the conditions found in many of the stands. Most stands are younger, denser and actively undergoing thinning, with the result that the trees should tend to be less tapered.

The **tree species** distribution reflects both the successional status of the forest in the area and the overall climatic conditions established by changes in elevation. The forest in this area is primary successional with secondary successional species beginning to appear. Aerial photography indicated that there was a predominance of *Pinus contorta* in the upper and mid-elevations with increasing amounts of *Populus tremuloides* in the lower elevations. Secondary succession was to *Picea engelmannii x glauca* with lesser amounts of *Abies lasiocarpa*. *Picea mariana* dominated on the wetter sites. As *Pinus contorta* was a major constituent of the forest, the distribution of the all-species data set was skewed in the same direction as the *Pinus contorta* data set.

The differences in mean **stem-form** for *Pinus contorta* and *Picea engelmannii x glauca* (Table 2) were consistent with the findings of Clyde and Titus (1987). *Picea engelmannii x glauca*, which is shade-tolerant and often originated in the understory, tended to be more tapered than *Pinus contorta*, a primary successional species. *Picea mariana*, which is secondary successional species, should have displayed values closer to those of *Picea engelmannii x glauca*. The discrepancy probably lies in the fire history of the area. The **tree age** distribution for *Picea mariana* indicated that these were younger trees, probably originating at the same time as the sample

trees for *Pinus contorta* and not as secondary successional trees. The mean **tree age** for *Picea engelmannii x glauca* was 106.9 years and the mean **tree age** for *Picea mariana* was 88.0 years. The distributions for the **total number of stems** indicated that the sample trees for *Picea mariana* came from denser stands (mean value 2880.5 trees per hectare) than *Picea engelmannii x glauca* (mean value 1395.4 trees per hectare). The sample trees for *Picea mariana* came from stands which were more actively growing and thinning than the *Picea engelmannii x glauca* stands, which may account for some of the difference in the **stem-form.**

5.1.3 **Stand-closure**

The two measures of **stand-closure** displayed some correlation but in the final regression, the **total number of stems** contributed more than the **total basal area** to the prediction of **stem-form.** The **tree species** distributions for the **total number of stems** were similarly skewed to the **tree species** distributions for the **stem-form;** they followed the distributions associated with young primary successional stands where extensive thinning was taking place. The involvement of the variable associated with fallen **dead wood** for some species (*Pinus contorta* and *Betula papyrifera*) suggested that active thinning was associated with less tapered trees. This may have been due to two factors; a domino effect and a destabilization effect. The domino effect occurred when the collapse of a tree within a stand resulted in damage to the surrounding trees from impact. The destabilization effect resulted from rapid opening of the stand and increased wind force on the remaining trees which did not have time to accommodate the change. Standing **dead stems** did not directly affect the **stem-form;** the relationship between **dead**

stems and **stem-form** disappeared with the inclusion of the **stand-closure** variables. The lack of involvement of standing **dead stems** in the prediction of **stem-form** suggested that as long as the dead trees remained standing, they served as partial windbreaks.

5.1.4 **Site-conditions**

Although larger sample sizes would have qualified the data sets for *Larix laricina*, *Betula papyrifera* and *Populus balsamifera* as large populations, it is not true that more conclusive results would have been achieved. These species were under-represented in the study area and occurred under very specific **site-conditions.** In view of the selective method of sampling, it is probable that all of the variation in the population within the study area was contained within a small sample. *Larix laricina* was highly intolerant of competition, occupied the wettest sites and did not appear at high elevations. *Betula papyrifera* and *Populus balsamifera* occupied the same sites as *Populus tremuloides; Populus tremuloides* had substantial competitive advantage with its ability to clone, a trait stimulated particularly through elevated soil temperatures (Steneker, 1974) which may have been associated with the occurrence of light ground fires. Consequently *Betula papyrifera* and *Populus balsamifera* were only found on those sites where *Populus tremuloides* was excluded; these sites were likely subjected to periodic surface or subsurface inundation (Kocaoglu and Jaques Bennett, 1983 pg 66).

5.2 Statistical Design

The analysis of the data involved designing statistical procedures to test whether a hierarchical **stem-form/stand-closure/-site-conditions** relationship existed. In order to achieve this,

the stepwise regression analysis of the relationships was preceded by several procedures designed to simultaneously reduce the number of variables and eliminate the complications introduced into the analysis by multicollinearity. The variables were handled consistently across the **tree species** data sets to allow for inter-species comparisons. This approach did not eliminate multi-collinearity within the species data sets for these variables and complications arose as a result.

The regression analysis of the remaining variables could have been performed utilizing any one of several variations of the procedure. Of the four options, all possible, forward selection, backward elimination and stepwise forward selection, stepwise selection was chosen. This procedure produced a fairly objective result. Each variable was entered and checked for its contribution to the relationship. Then all variables were rechecked with the addition of each new variable to ensure the most representative and concise relationship. There were several problems associated with this procedure, including over-fitting of data, too many variables and capitalization on chance.

The examination of the residuals for autocorrelation suggested that some positive autocorrelation did exist and a best fit for some regression equations was not achieved.

5.2.1 Multicollinearity

The use of principal components analysis to screen variables was primarily to remove groups of highly correlated variables. Multicollinearity occurs when the independent variables are very highly inter-correlated and its presence results in both logical and statistical problems (Tabachnick and Fidell, 1989 pg 87-88).

The problems associated with regression (undefined F values; r=1.000) were likely due to multicollinearity in the *Larix laricina*, *Betula papyrifera* and *Populus balsamifera* site data. To facilitate inter-species comparisons, a consistent set of **site-conditions** variables was included in the analysis. This set was retained for all of the species data sets despite obvious correlation between the variables for some species. High correlation among **site-conditions** variables within the *Larix laricina*, *Betula papyrifera* and *Populus balsamifera* data sets (correlation coefficients in excess of 0.90) did not translate into high correlation within other species data sets. There was sufficient evidence in this exploratory analysis to suggest that the **stem-form/stand-closure/site-conditions** relationship should be handled separately for each species. Consistent treatment of major variables such as the **stem-form**, **total number of stems** and **elevation** did not result in multicollinearity problems but other variables should be evaluated and eliminated on a species by species basis.

5.2.2 Stepwise Regression

The stepwise forward selection of variables was utilized as the most objective means of determining which of the **site-conditions** variables contributed significantly to the prediction of the **stem-form** and the **stand-closure** variables. While this procedure treats the contribution of each variable the most objectively, there is a tendency to overfit the model with too many variables (Verbyla, 1989). In this study, the result may have been the inclusion of biologically redundant variables. A cursory examination of the **stem-form/stand-closure/site-conditions** relationship without the inclusion of the categorical variables suggests that

this was true in this study. The removal of the categorical variables did not result in large differences in the multiple correlation coefficients.

For any regression analysis, whether forward selection, backward elimination or stepwise, the order of entry of the variables may result in changes in the final equation and the associated multiple correlation coefficient. There were changes in the multiple correlation coefficient observed for *Pinus contorta* when the **total basal area** was included in the analysis of the **stem-form/site-conditions** relationship. Although the **total basal area** was not part of the final equation, its initial inclusion affected which variables were entered thereafter.

There are also regression problems where results are computed from a single sample, according to Tabachnick and Fidell (1989 pg 147). The results may be more due to chance and cannot be translated where decisions on variables are being made based on potentially minor differences in statistics computed from a single sample. Cross-validation with a second sample would have assisted in verification of the results.

5.2.3 Autocorrelation

The presence of autocorrelation within the residuals suggests that the relationship tested was not the most representative; the regression equation was not the best fit. Autocorrelation was detected for most of the residuals from the regression equations for the **stand-closure/site-conditions** relationship. The presence of autocorrelation was not consistent across the species data sets. Autocorrelation was detected for the residuals from the regression equations for the **stem-form/site-conditions** relationship for

Populus tremuloides. Similarly, autocorrelation was detected for the residuals from the regression equations for the **stem-form/site-conditions+total basal area** relationship for *Populus tremuloides*. No autocorrelation was detected for the residuals from the equations for the **stem-form/site-conditions+total number of stems** relationship.

Positive autocorrelation that was not consistent across the species data sets may be the result of transformations performed across the species data sets, particularly with respect to the **site-conditions**. Transformations specific to each species data set might be more effective in producing a representative regression equation. The inclusion of **total number of stems** with the **site-conditions** removes the positive autocorrelation in the **stem-form/site-conditions** relationship. The inclusion of **total number of stems** reduces the number of **site-conditions** variables; this suggests that the problems with autocorrelation may be related to the **site-conditions** variables only.

5.3 **Stem-form/Stand-closure/Site-conditions** Relationship

There are two aspects to the **stem-form/stand-closure/site-conditions** relationship. It can be examined as a comparison across species for each component relationship and as a comparison of the component relationships within each species. The component relationships consist of the **stand-closure/site-conditions** relationship, the **stem-form/stand-closure** relationship and the **stem-form/site-conditions** relationship. The variables that define these relationships consist of the **stem-form**, the two **stand-closure** variables, the macro **site-conditions** variables, meso **site-conditions** and micro **site-conditions** variables (Figure 9).

SPECIES	STAND–CLOSURE/ SITE–CONDITIONS TBA TNS MACRO MESO MICRO	STAND–CLOSURE/ STEM–FORM TBA TNS	STEM–FORM/ SITE–CONDITIONS MACRO MESO MICRO	STEM–FORM/ STAND–CLOSURE/ SITE–CONDITIONS TBA TNS MACRO MESO MICRO
Pinus contorta	positive significant	negative significant	positive significant	positive significant
Picea mariana	positive significant	negative significant	positive signficant	positive signficant
Picea engelmannii 'x' glauca	positive significant	negative significant	positive significant	positive significant
Abies lasiocarpa	positive significant	negative not significant (TNS)	positive significant	positive significant
Larix laricina	positive F undefined (TNS)	positive not significant	zero	zero
Populus tremuloides	positive significant	negative not significant (TBA)	positive significant	positive significant
Betula papyrifera	positive F undefined (TNS)	positive not significant	positive significant	positive significant
Populus balsamifera	positive significant	negative not significant (TBA)	positive significant	positive significant
All–species	positive significant	negative signficant	positive signficant	positive signficant

TNS = total number of stems
TBA = total basal area

MACRO = macro site–conditions
MESO = meso site–conditions
MICRO = micro site–conditions

'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations

Figure 9
Stem-form / Stand-closure / Site-conditions Relationships by Species

5.3.1 **Stand-closure/Site-conditions**

The examination of the multiple correlation coefficients between the **site-conditions** variables and the two **stand-closure** variables, **total basal area** and **total number of stems**, indicated that there was a significant relationship for most species. The overall relationship was a positive one but as this was a multiple regression, individual **site-conditions** variables may have had a negative relationship with **stand-closure**.

Pinus contorta, *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa* and *Populus tremuloides* produced correlation coefficients that were significantly different from 0.000. The results for both **stand-closure** variables for *Larix laricina*, *Betula papyrifera* and *Populus balsamifera* were not significantly different from 0.000; the small sample size and limited conditions that were sampled are the most likely reasons for the questionable results. For *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa* and *Populus tremuloides*, the **site-conditions** were predictors of the **stand-closure**. For *Larix laricina*, *Betula papyrifera* and *Populus basamifera*, the **site-conditions** may have been predictors of the **stand-closure** but this was not reliably established by this analysis.

The examination of the range of correlation coefficients suggested that there was not a substantial difference in the degree to which the **site-conditions** predicted the **total basal area** versus the **total number of stems**. Both sets of coefficients were similar in magnitude although, as the partial correlation coefficients (Appendix B) indicated, there were different **site-conditions** involved in predicting each of the two measures of **stand-closure**.

The individual **site-conditions** variables involved in predicting **stand-closure** varied considerably between the **total basal area** and the **total number of stems** (Appendix B) and also by the **tree species**. **Ecoregion**, a macro variable, and **plant association** were frequent predictors of both measures of **stand-closure**; there was no consistency as to which categories of **ecoregion** and **plant association** were predictive and which were not. Other **site-conditions** variables were less consistent between the **total basal area** and the **total number of stems**.

Of the meso variables, the **tree age** was consistently involved in the prediction of **total basal area**. The involvement of the **tree age** was less consistent with the **total number of stems**; the **total number of stems** for *Picea engelmannii x glauca* and *Abies lasiocarpa* was not predicted by the **tree age**. *Picea engelmannii x glauca* and *Abies lasiocarpa* originated as secondary successional understory **tree species** in the study area with random factors such as the seed source playing a role in the stand density. For the primary successional **tree species**, *Pinus contorta*, *Populus tremuloides* and *Populus balsamifera*, the proportion of standing **dead stems** positively predicted the **total number of stems**. This was most likely an indication of dense, actively-thinning stands.

There was no consistent involvement of the micro variables in the prediction of both of the **stand-closure** variables for all **tree species**. For the hardwood species, *Populus tremuloides*, *Betula papyrifera* and *Populus balsamifera*, a finer **soil texture** was associated with a decrease in the **total basal area**. For *Picea engelmannii x glauca*, *Abies lasiocarpa* and *Populus balsamifera* increased soil moisture (a higher value for **soil drainage**) was

associated with an increase in the **total basal area** and the **total number of stems**. For **total number of stems**, this effect was also present for *Populus tremuloides*. For **total number of stems**, the effect was negated by a condition of **wetland** sites if the **tree species** was able to inhabit these sites.

5.3.2 **Stem-form/Stand-closure**

There were essentially two aspects to the **stem-form/stand-closure** relationship, the differences between species and the relationship between variables. The examination of the correlation coefficients for the **stem-form/stand-closure** relationship indicated that there was a significant relationship for most **tree species**. It was not possible to obtain statistically significant results for some **tree species**. The results for *Larix laricina* and *Betula papyrifera* were not significant for both measures of **stand-closure**. The results for *Populus tremuloides* and *Populus balsamifera* were not significant for the **total basal area**. The results for *Abies lasiocarpa* were not significant for the **total number of stems**.

The consistency in the magnitude and direction of the correlation coefficients for the **stem-form/stand-closure** relationship for all **tree species** with the exception of *Larix laricina* suggested that this was not a phenomenon unique to a single species or group of species. For all species with the exception of *Larix laricina*, as the **stand-closure** increased, the trees became thinner relative to their height. This relationship was consistent regardless of which measure of **stand-closure** was used. An increase in the **total basal area** or the **total number of stems** resulted in a decrease in the taper. This was consistent with the mechanistic theory on **stem-form;** increased basal thickening resulted as each

individual tree stabilized against wind force. The reason that this effect was reversed for *Larix laricina* may lie in the extremely wet sites that *Larix laricina* normally inhabits. It is likely that low stand densities were also reflecting the poor conditions for growth; wind exposure may have been less limiting than germination and survival under very water-logged conditions.

For the **stem-form** and the **total basal area**, *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca* and *Abies lasiocarpa* produced correlation coefficients that were significantly different from 0.000. The deciduous species, *Larix laricina*, *Populus tremuloides*, *Betula papyrifera* and *Populus balsamifera*, produced correlation coefficients that were not significantly different from 0.000. For the evergreen coniferous species, *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca*, the **total basal area** was a predictor of the **stem-form**. For the deciduous species, *Populus tremuloides*, the **total basal area** was not a predictor of the **stem-form**. The results for the deciduous coniferous species, *Larix laricina*, were not significant due to small sample size; there may be a relationship but this analysis could not establish that. The results for *Betula papyrifera* and *Populus balsamifera* were also not significant due to small sample size, although the magnitude of the correlation coefficients would suggest that, as with *Populus tremuloides*, the **total basal area** was not a predictor of the **stem-form**. It was most likely that the **total basal area** was a predictor of the **stem-form** for the gymnosperms (conifers) but not for the angiosperms (non-conifers).

For the **stem-form** and the **total number of stems** the correlation coefficients for *Pinus contorta*, *Picea mariana*, *Picea*

engelmannii x glauca, *Populus tremuloides* and *Populus balsamifera* were significantly different from 0.000. For *Abies lasiocarpa*, *Larix laricina* and *Betula papyrifera*, the **total number of stems** may help to predict the **stem-form** but this was not established conclusively by this analysis.

An examination of the range of correlation coefficients suggested that there was a difference in the degree to which the **stem-form** was predicted by the **total basal area** versus the **total number of stems**. Both sets of coefficients were similar in magnitude for the gymnosperms but the coefficients were substantially lower for the **total basal area** for the angiosperms. Overall, the **total number of stems** was a better predictor of the **stem-form** than the **total basal area**.

5.3.3 **Stem-form/Site-conditions**

The multiple correlation coefficients for the **stem-form/site-conditions** relationship indicated that there was a significant relationship for all species except *Larix laricina*. The overall relationship was a positive one but as this was a multiple regression, individual **site-conditions** variables may have a negative relationship with the **stem-form**. The results for *Larix laricina* indicated that there was no significant **stem-form/site-conditions** relationship; the small sample size and limited conditions that were sampled made the results unreliable. For *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa* and *Populus tremuloides*, *Betula papyrifera* and *Populus balsamifera*, the **site-conditions** were predictors of the **stem-form**.

The individual **site-conditions** variables involved in predicting **stem-form** varied considerably between species. **Elevation**,

sometimes in combination with **ecoregion**, both macro variables, were frequent predictors of **stem-form**. Of the meso variables, **tree age** was sometimes predictive but the effect was not consistent. The micro variables and **plant associations** were not consistently involved in the prediction of the **stem-form**.

5.3.4 **Stem-form/Stand-closure/Site-conditions**

An examination of the multiple correlation coefficients for the **stem-form/stand-closure/site-conditions** relationship yielded consistent results for the larger data sets. For *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa*, *Populus tremuloides* and the all-species data sets there was no exclusive **stem-form/stand-closure** or **stem-form/site-conditions** relationship; both the **stand-closure** and the **site-conditions** help to predict the **stem-form**. Basal thickening in a tree stem in response to increased wind force was not a simple phenomenon. This was consistent with previous studies regarding the **stem-form/site-conditions** relationship. The **stand-closure** variables did not help to predict **stem-form** when **site-conditions** were included for *Larix laricina*, *Betula papyrifera* and *Populus balsamifera*. These data sets were smaller and the range of conditions was more limited than for the larger data sets.

A comparison of the results of the multiple regression for the **stem-form/site-conditions** relationship and the **stem-form/stand-closure/site-conditions** relationship indicated that including the **stand-closure** variables strengthened the relationship or made no difference (Table 6). There was one discrepancy; for *Picea engelmannii x glauca*, the addition of the **stand-closure** variables produced a slightly lower correlation coefficient. The initial

inclusion of a **stand-closure** variable, **total number of stems**, altered the order and entry of the **site-conditions** variables and produced a slightly different result.

The inclusion of the **total number of stems** in the **stem-form/site-conditions** relationship did not exclude all of the **site-conditions** variables in the prediction of the **stem-form**. **Elevation** and/or **ecoregion**, both macro variables, were frequent predictors of the **stem-form**. This effect varied depending upon the **tree species** involved. For *Larix laricina* and *Betula papyrifera* the**stem-form** was unaffected by both **elevation** and **ecoregion**; this emphasized the limited range of **site-conditions** that these species occupy.

Although the **total number of stems**, a meso variable, was fairly consistently involved in the prediction of the **stem-form**, it was occasionally modified by the stand composition in terms of the **tree form**. It was also variable by **tree species**. The correlation coefficients for the all-species data set indicated that there was less taper with more stems per hectare but this was modified by the presence of conical evergreens. A higher percentage of conical evergreens reduced the effect of increased **stand-closure**. This may have been due to the inherently higher values for **stem-form** for *Picea engelmannii x glauca* (Table 2), which was a larger data set and a major component of the all-species data set. The change in conformation of the tree foliage may have also had an effect; a conical tree intercepts less wind at the tip of the crown and may provide less of a windbreak for other species present. This may result in basal thickening for the other **tree species** present.

There was no consistency in the involvement of the micro, categorical or **plant association** variables. The all-species data

set involved more soil variables in the prediction of the **stem-form** than any of the other species data sets; these **site-conditions** variables may have been masking species differences.

For all species except *Larix laricina*, *Betula papyrifera* and *Populus balsamifera*, the **site-conditions** plus the **total number of stems** were partial predictors of the **stem-form** (Figure 10). The **total basal area** was not a predictor of the **stem-form** when included with the **site-conditions** variables. The individual **site-conditions** variables involved in predicting the **stem-form** differed when the **total number of stems** was included with the **site-conditions**. This suggested that at least some of the predictive ability of the **site-conditions** variables resided in the inter-relationship with the **total number of stems**, which in turn, helped to predict the **stem-form**. Figure 11 shows the breakdown in explained variance for the relationships and inter-relationships as two sets of pie charts, one for the **total basal area** and one for the **total number of stems**.

The inter-relationship between the **stand-closure** variables and the **site-conditions** variables within the **stem-form/stand-closure/-site-conditions** relationship indicated that the **total number of stems** was a more independent predictor of the **stem-form** than the **total basal area** (Figure 11). All of the variance accounted for by the correlation of the **stem-form** with the **total basal area** was accounted for by the **site-conditions** variables. An examination of the **site-conditions** variables involved in the prediction of the **total basal area** and the **site-conditions** variables involved in the prediction of the **stem-form** indicated that a few **site-conditions** variables were involved in the prediction of both; there was no

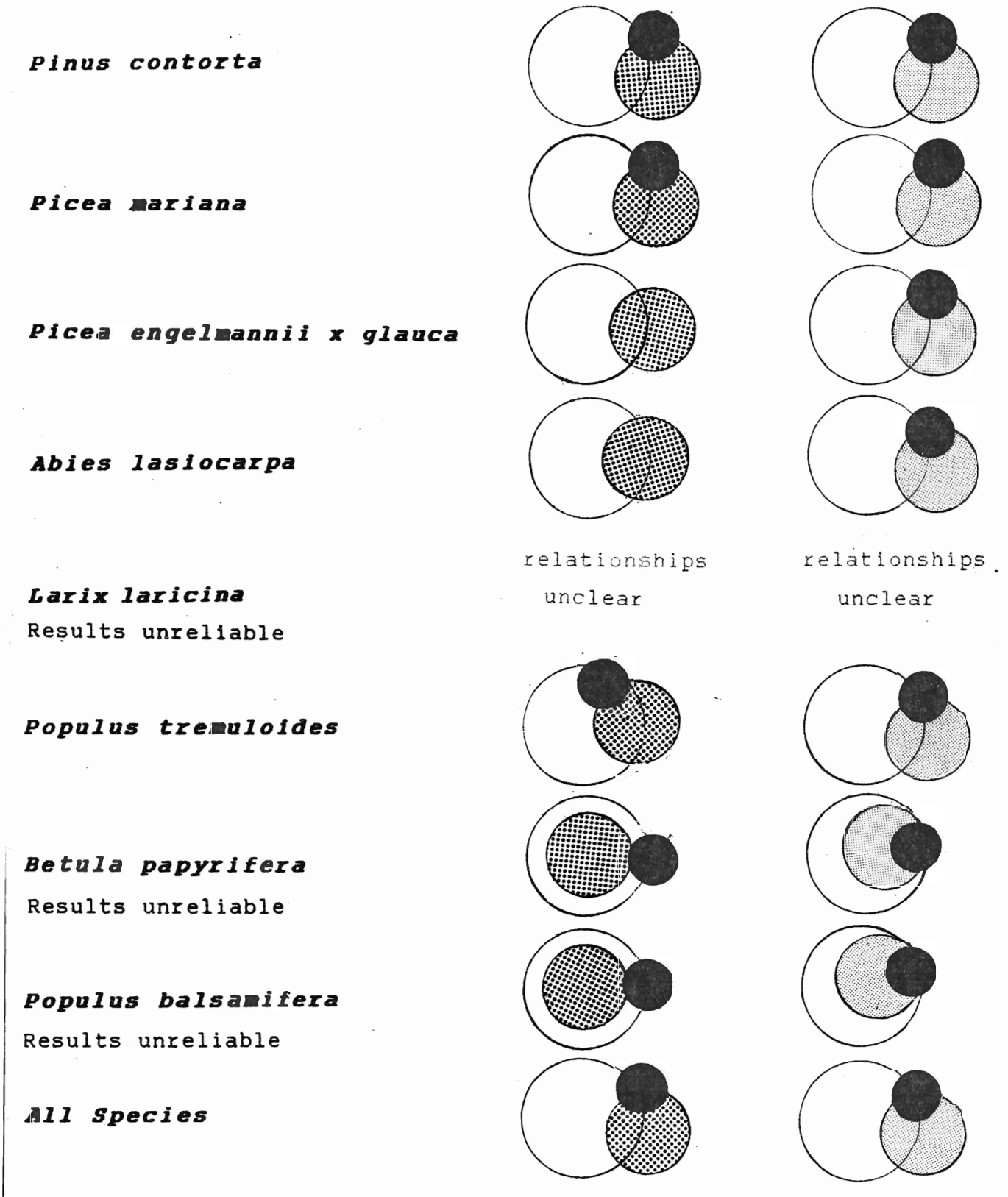


Figure 10
Venn Diagrams of Stem-form / Stand-closure / Site-conditions Relationship by Species

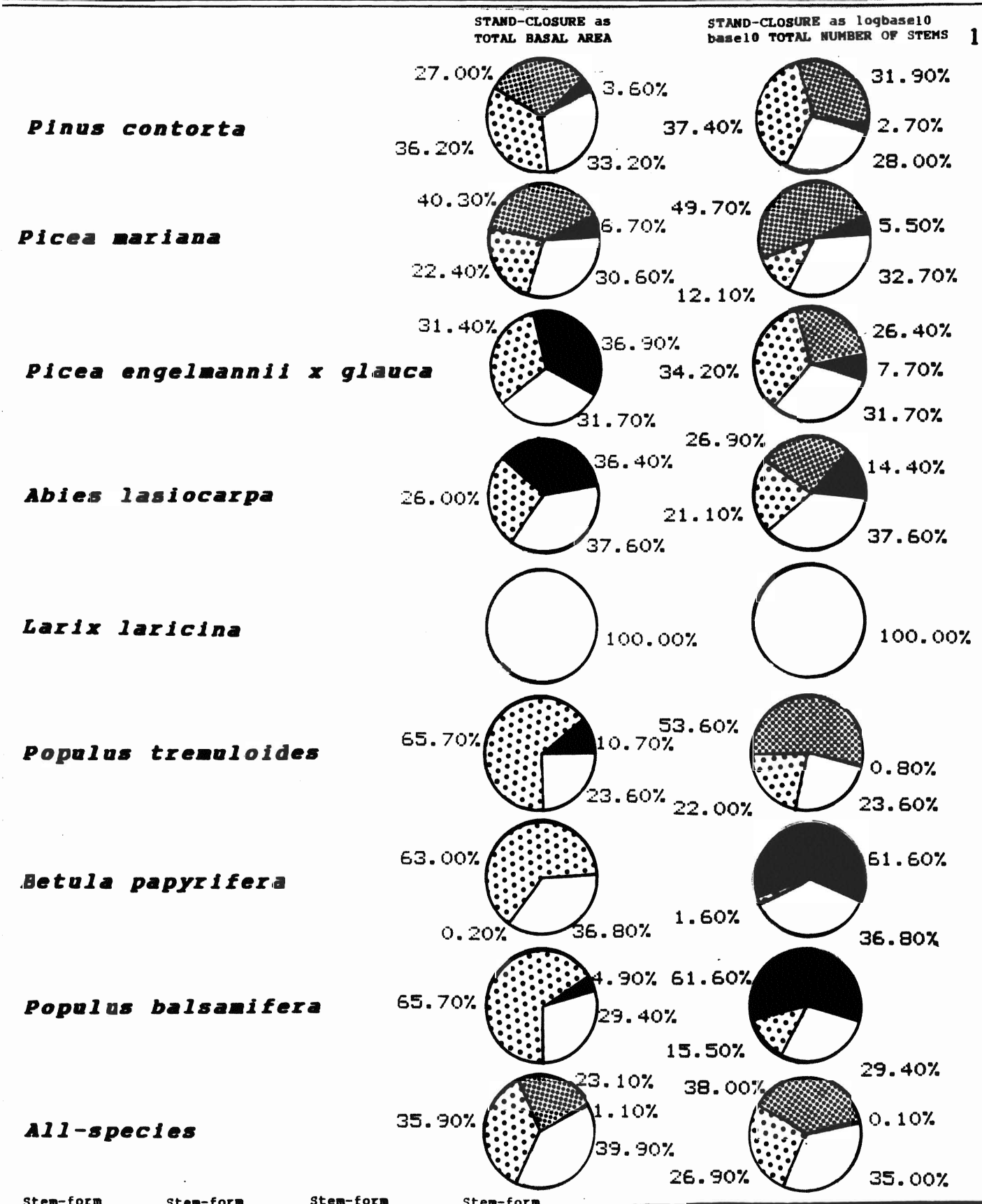


Figure 11

Pie Charts of Explained Variance - Stem - form / Stand - closure / Site - conditions Relationship by Species

consistency in the **site-conditions** variables involved from one species to the next.

The inter-relationship between the **total number of stems** and the **site-conditions** variables within the **stem-form/stand-closure/site-conditions** relationship was less consistent (Figure 11). For *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa* and *Populus tremuloides* there was very little inter-relationship; for *Larix laricina*, *Betula papyrifera* and *Populus balsamifera* all of the variance accounted for by the correlation of the **stem-form** with the **total number of stems** was also accounted for by the **site-conditions** variables. Significantly, these were also the species which had a limited sample size and a limited range of **site-conditions**. An examination of the **site-conditions** variables involved in the prediction of the **total number of stems** and the **site-conditions** variables involved in the prediction of **stem-form** indicated a few **site-conditions** variables were involved in predicting both; there was no consistency in the **site-conditions** variables involved from one species to the next.

5.3.5 Cross-comparison of Relationships

A cross-comparison of the variables across the component relationships can be conducted as a comparison of variables between **tree species**, a comparison of variables between the two measures of **stand-closure** and a comparison of the different **site-conditions** variables at the macro, meso and micro levels. In comparing the relationships, the data sets for *Larix laricina*, *Betula papyrifera* and *Populus balsamifera* produced results that were often not significantly different from 0.000. This was coincident with the

size of the data sets; all of these data sets were derived from less than 20 sites.

Figure 12 summarizes an overall trend across the **tree species** data sets in the number of variables for the **stem-form/site-conditions** relationship and the **stand-closure/site-conditions** relationship. For the **stem-form/site-conditions** relationship, the**stand-closure/site-conditions** relationship for both **stand-closure** variables, and the **stem-form/stand-closure/site-conditions** relationship for both **stand-closure** variables, the total number of variables was related to the size of the data set. The trend was clearest for the **stem-form/stand-closure/site-conditions** relationship utilizing **total number of stems.** Overall, the all-species data set had more **site-conditions** variables; this was the largest data set and the **tree species** differences in site preference were masked.

In comparing the two measures of **stand-closure,** the **total number of stems** was usually a better predictor of the **stem-form;** the **total basal area** was a better predictor of **stem-form** for *Picea engelmannii x glauca* and for *Abies lasiocarpa.* With the exception of *Picea engelmannii x glauca,* the **site-conditions** were better predictors of the **total basal area** than the **total number of stems.** The **site-conditions** plus the **total number of stems** was a better predictor of the **stem-form** than the **site-conditions** plus the **total basal area** with the exception of *Picea mariana* and *Picea engelmannii x glauca.* As *Picea mariana, Picea engelmannii x glauca* and *Abies lasiocarpa* were all evergreen, conical in form and potentially secondary successional species, the parameters associated

SAMPLE SIZES

SPECIES DATA SETS IN ORDER OF DECREASING SAMPLE SIZE

653		279		123		86		72		49		23		12		9
ALL	>	PL	>	SX	>	AW	>	SB	>	FA	>	PB	>	BW	>	LT

TOTAL BASAL AREA and SITE–CONDITIONS

SPECIES DATA SETS IN ORDER OF DECREASING NUMBER OF VARIABLES

ALL	>	PL	=	PB	>	SX	>	AW	>	FA	>	BW	>	SB	>	LT

TOTAL NUMBER OF STEMS and SITE–CONDITIONS

SPECIES DATA SETS IN ORDER OF DECREASING NUMBER OF VARIABLES

ALL	>	PL	>	SX	>	AW	>	BW	>	FA	=	PB	>	SB	>	LT

STEM–FORM and SITE–CONDITIONS

SPECIES DATA SETS IN ORDER OF DECREASING NUMBER OF VARIABLES

ALL	>	PL	>	SX	>	AW	=	SB	>	PB	>	FA	=	BW	>	LT

STEM–FORM and SITE–CONDITIONS + STAND–CLOSURE (BOTH VARIABLES)

SPECIES DATA SETS IN ORDER OF DECREASING NUMBER OF VARIABLES

ALL	>	PL	>	AW	>	SX	>	SB	=	FA	=	PB	>	BW	>	LT

STEM–FORM and SITE–CONDITIONS + TOTAL BASAL AREA

SPECIES DATA SETS IN ORDER OF DECREASING NUMBER OF VARIABLES

ALL	>	PL	=	SX	>	AW	=	SB	>	PB	>	FA	=	BW	>	LT

STEM–FORM and SITE–CONDITIONS + TOTAL NUMBER OF STEMS

SPECIES DATA SETS IN ORDER OF DECREASING NUMBER OF VARIABLES

ALL	>	PL	>	SX	>	AW	>	SB	=	FA	=	PB	>	BW	>	LT

PL = *Pinus contorta*
SB = *Picea mariana*
SX = *Picea engelmannii x glauca*
FA = *Abies lasiocarpa*
LT = *Larix laricina*
AW = *Populus tremuloides*
BW = *Betula papyrifera*
PB = *Populus balsamifera*
ALL= All–species

Figure 12
Sample Size versus Number of Site-conditions Variables by Species

with these species might be expected to differ from the other **tree species**.

The **site-conditions** variables differed substantially in their individual contributions to the prediction of the **stand-closure** and the **stem-form**. **Ecoregion**, a macro **site-conditions** variable was consistently involved in the prediction of both variables. There were no meso **site-conditions** variables involved in the prediction of the **stand-closure** and the **stem-form**. Of the micro **site-conditions** variables, the presence of exposed **mineral soil**, fallen **dead wood** and **wetland** were frequently involved in the prediction of both variables.

5.4 **Stem-form** and Wind

The results of this study have implications in the understanding of the relationship between **stem-form** and wind adaptation, in the understanding of tree stem adaptation, stem adaptation, biomechanical adaptation, adaptation in general and in the understanding of the relationship between plants and their environment. The **stem-form/stand-closure/site-conditions** relationship illustrates the complexity of response under uncontrolled conditions. The strength of the relationships between these variables is not high but this emphasizes the role that random factors play in natural phenomena.

5.4.1 **Stem-form** and Wind Adaptation

The mechanistic theory of **stem-form** indicates that the stem conformation develops as a stabilization against two forces; a horizontal wind force and a vertical gravititational force. An increase in either of these two forces should produce a broader base relative to the height of the tree. The impact of gravity is

much less than the effect of wind sway until the tree stem becomes very large; wind sway is the most critical factor in producing a change in the **stem-form.** The amount of wind force on an individual tree is a result of the climate and topography at the macro level and the stand density and composition at the meso level. The ability of the tree to respond to increased wind force is determined by the soil conditions at the micro level, the genetics of the species and by random events associated with the stand history.

The presence of a significant **stem-form/stand-closure** relationship illustrates the effect of increased wind force on each individual tree within a stand. As the **total number of stems** becomes less, there is more basal thickening to compensate for the increased wind on each tree. As the **total basal area** does not have a direct relationship with the basal thickening in each tree due to wind force, it can be assumed that the **total basal area** is a reflection of the overall wind force, which is fairly consistent; the presence of many small diameter trees is essentially the same phenomenon as a few large diameter trees as far as wind force is concerned.

The **stem-form/site-conditions** relationship is likely a reflection of root stabilization and changes in biomass allocation. Changes in biomass allocation under environmental stress may result from carbon allocation being directed away from the stem to other structures such fine roots. As a result, height gain and the need for diameter increase may both be affected. The relationship between the **stem-form** and **elevation** is possibly based on a need for increased sapwood area. In the upper elevations and higher latitudes, where conditions are severe and the growing season is

limited, trees have a greater diameter relative to their height.

5.4.2 Tree Stem Adaptation

The differences in response to increased wind force based on **tree species** are likely a reflection of the inherent **stem-form** and the specific **site-conditions** that cause stress. The impact of increased wind force on evergreen **tree species** such as *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca* and *Abies lasiocarpa* is different than on deciduous **tree species** such as *Larix laricina*, *Populus tremuloides*, *Betula papyrifera* and *Populus balsamifera*. The evergreen tree retains its foliage all year and hence has more overall aerodynamic drag than a deciduous tree. The impact of increased wind force will be greater for those **tree species** which have a rounded crown than for those species that are conical in shape. Consequently *Pinus contorta*, *Populus tremuloides*, *Betula papyrifera* and *Populus balsamifera* would sustain more wind force than *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa* and *Larix laricina*. Lastly, **tree species** which are adapted to different **site-conditions** will undergo stress under different environmental conditions and respond differently to increased wind force, particularly in terms of changes in biomass allocation. Wet conditions will affect the response of dryland species such as *Pinus contorta* differently than mesic species such as *Populus tremuloides*, *Picea engelmannii x glauca* and *Abies lasiocarpa* or wetland species such as *Larix laricina* and *Picea mariana*.

5.4.3 Stem Adaptation

The involvement of **plant association** in the **stem-form/stand-closure/site-conditions** relationship demonstrates that the stand origins affect the manner in which the **stem-form** responds to

increased wind force. The initial competition from other understory species in terms of germination and survival results in a long-term effect on the ability of the tree to respond to wind sway.

5.4.4 Biomechanical Adaptation

The presence of unexplained variance in the **stem-form/stand-closure/site-conditions** relationship may lie in the impact of random climatic occurrences. The presence of high winds and/or rapid thinning may result in the production of compression or tension wood. A single gale will produce dramatic changes in the orientation of the stem and mask some of the basal thickening that would normally accompany increased wind force.

5.4.5 Adaptation

The presence of a **stem-form/stand-closure** relationship, modified by the **site-conditions** is an example of a complex biomechanical plant adaptation. Biochemical plant adaptation to these types of conditions take the general form of changes in ethylene production in response to a physical disturbance. The response to increased wind sway is the same as the response to shaking. Siesmomorphogenesis, the response to shaking induced by earthquakes results in ethylene production and the inhibition of auxin transport (Salisbury and Ross, 1992 pg 415).

5.4.6 Relationship Between Plants and Environment

The direct involvement of the **site-conditions** variables in the prediction of **stem-form** is an indication that plant growth is not always a direct response to a particular stimulus. In this case, the response to the stimulus, which is increased wind force through less **stand-closure**, is mediated by the conditions that the plant is

growing under. The resources available to the plant through the macro, meso and micro **site-conditions** limit the growth of the plant and change the ability of the plant to physically respond to a simple stimulus. The in vitro theory is not consistent with the in vivo response.

The complexity of the response of the **stem-form** to the **stand-closure** results from deterministic factors found in the **stand-closure** and the **site-conditions**. The fairly consistent involvement of the **total number of stems** and **elevation** suggests that there are measureable and predictable factors involved in the relationship between the **stem-form**, the **stand-closure** and the **site-conditions**. Resource scarcity, in the form of poor **site-conditions**, exerts a greater influence on both **stand-closure** and **site-conditions** than unmeasured and/or unpredictable factors. The amount of unexplained variance in the **stem-form** suggests that there are many unmeasured and/or unpredictable factors involved in the relationship between plants and the environmental conditions present. The involvement of factors that reflect stand history such as **plant association** indicates that stochastic factors may play a significant role in the prediction of the **stem-form**.

6. CONCLUSIONS

The **stem-form/stand-closure/site-conditions** relationship is best described as outcome 8 (Figure 6) for those **tree species** with reliable results. The specific relationships for each **tree species** are depicted as Venn diagrams with appropriate variations on the original outcome (Figure 10).

The **stand-closure** partially predicts the **stem-form** and the **site-conditions** partially predict both the **stem-form** and the **stand-closure** independently. A decrease in stand density, due in part to environmental conditions, is reflected as an increase in wind force on the individual trees and an increase in the stem taper. Environmental conditions also directly affect the stem taper. The individual components of this overall conclusion are summarized as follows.

6.1 Measures of **Stand-closure**

There were four measures of **stand-closure** utilized. These were **crown closure**, **total number of stems**, **total basal area** and **total volume**. The **crown closure** is the density of the foliage in the overstory. The **total number of stems** is the stand density, including standing dead stems. The **total basal area** is the total area of live wood at breast height. The **total volume** is the total volume of live wood.

6.2 Presence of Tree Species

There were eight **tree species** present in the study area. These included *Pinus contorta* (279 samples), *Picea mariana* (72 samples), *Picea engelmannii x glauca* (123 samples), *Abies lasiocarpa* (49 samples), *Larix laricina* (9 samples), *Populus tremuloides* (86 samples), *Betula papyrifera* (12 samples) and *Populus balsami-*

fera (23 samples). *Picea engelmannii x glauca* was a composite of *Picea engelmannii* at the higher elevations and *Picea glauca* at the lower elevations and all of the intergrades in between. As the sample sizes for *Larix laricina* and *Betula papyrifera* were less than 20, significant results for these species were not easily obtained. *Populus balsamifera* was a larger data set but was derived from a limited number of sites and was subject to the same limitations.

6.3 Tree Species Variation in **Stem-form**

The **stem-form** represents the conformation of the tree stem. It was calculated as a simple ratio, the diameter at breast height (1.3m) to the total tree height. A higher value for the **stem-form** indicates a greater taper. There was a difference in the mean **stem-form** based on **tree species**. These species ranged from the highest mean value to the lowest mean value for the **stem-form** in the following order: *Picea engelmannii x glauca* (1.384), *Picea mariana* (1.271), *Abies lasiocarpa* (1.271), *Pinus contorta* (1.268), *Populus balsamifera* (1.172), *Populus tremuloides* (1.159), *Larix laricina* (1.153) and *Betula papyrifera* (1.079).

6.4 Correlation between Measures of **Stand-closure**

All four of the measures of **stand-closure** (**crown closure**, **total number of stems**, **total basal area** and **total volume**) were not statistically independent. The correlations between the **crown closure** and the **total number of stems**, the **crown closure** and the **total basal area** and the **crown closure** and the **total volume** were not significantly less than 0.950 for *Larix laricina*. The correlation between the **total basal area** and the **total volume** was not significantly less than 0.950 for *Picea mariana*, *Larix*

laricina, *Populus tremuloides* and *Betula papyrifera*. Both the **crown closure** and the **total volume** were dropped as indicators of the **stand-closure**. Only the **total number of stems** and the **total basal area** were retained.

6.5 **Stem-form/Stand-closure** Relationship

There was a statistically significant **stem-form/stand-closure** relationship. This relationship varied in levels of significance, magnitude and direction by species, although there was an overall trend of increasing values for **stem-form** with decreasing values for **stand-closure**. This relationship also varied between the two measures of **stand-closure**, the **total number of stems** and the **total basal area**. The **total number of stems** was a slightly better predictor of the **stem-form** than the **total basal area**, particularly for the deciduous species, *Larix laricina*, *Populus tremuloides*, *Betula papyrifera* and *Populus balsamifera*.

6.6 **Stand-closure/Site-conditions** Relationship

There was a **stand-closure/site-conditions** relationship. This relationship varied in the **site-conditions** variables involved and in magnitude by species. As the **site-conditions** were analyzed simultaneously as a number of variables, the **stand-closure/site-conditions** relationship was always positive. This relationship did not vary substantially between the two measures of **stand-closure**, the **total number of stems** and the **total basal area**. The number of **site-conditions** that predict **stand-closure** roughly increased with the size of the species data set.

6.7 **Stem-form/Site-conditions** Relationship

There was a **stem-form/site-conditions** relationship. This relationship varied in the **site-conditions** variables involved and

in magnitude by species. As the **site-conditions** were analyzed simultaneously as a number of variables, the **stem-form/site conditions** relationship was always positive. The number of **site-conditions** variables that predict the **stem-form** roughly increased with the size of the species data set.

6.8 **Stem-form/Stand-closure/Site-conditions** Relationship

There was a **stem-form/stand-closure/site-conditions** relationship. This relationship varied in the **site-conditions** variables involved and in magnitude by species. The **stem-form/stand-closure/site-conditions** relationship demonstrated an overall but inconsistent improvement over the **stem-form/site-conditions** relationship. As the **site-conditions** plus the **stand-closure** were analyzed simultaneously as a number of variables, the relationship with the **stem-form** was always positive. This relationship also varied between the two measures of **stand-closure**, the **total number of stems** and the **total basal area**. The **total number of stems** usually produced a stronger relationship. The examination of the inter-relationship between the **total number of stems** and the **site-conditions** indicated that the **total number of stems** was an independent predictor of the **stem-form**. The examination of the inter-relationship between the **total basal area** and the **site-conditions** indicated that the **total basal area** was not an independent predictor of the **stem-form**. The number of **site-conditions** variables (when the **stand-closure** variables were included) that predict the **stem-form** increased directly with the size of the species data set.

In conclusion, there was a **stem-form/stand-closure/site-conditions** relationship. The **site-conditions** helped to predict

both the **stand-closure** and the **stem-form**. The **stand-closure** helped to predict the **stem-form**. None of these relationships were absolute; there were significant differences from total prediction. Consequently there are stochastic and/or other deterministic factors involved in the prediction of both the **stem-form** and the **stand-closure**. The deterministic factors that were included in this study contributed more to the prediction of the **stem-form/-stand-closure/site-conditions** relationships than stochastic and/or other deterministic factors. These relationships were not exactly the same for all **tree species**. Consequently there are genetic factors involved in the prediction of both the **stem-form** and the **stand-closure**.

Wind sway, while a significant deterministic factor in the conformation of the tree stem, has been illustrated to be compromised by other factors. The ability of the tree stem to stabilize with increased diameter in proportion to height in response to increased wind force in a more open stand is limited. Site factors, particularly more severe conditions associated with increased elevation, compromise the relationship. In addition, genetic factors associated with the species determine the inherent tree stem conformation. All of these factors do not together produce a predictable tree stem; a substantial amount of the variation is left unexplained. Although many site factors were included in this study, it is possible that other unmeasured factors, such as specific nutrient levels, are responsible. It is also possible and very likely that random factors associated with the stand history are responsible for the unexplained variation.

The involvement of a site factor such as fallen wood suggests

that the timing, speed and extensiveness of thinning may help to explain the response of an individual tree to increased wind force. A catastrophic thinning may produce an entirely different response than a gradual thinning.

Natural systems do not follow a strict hierarchical regimen of climatic factors superimposed on neighborhood factors superimposed on local factors; there is feed-back between and within all of these levels of influence. This complexity in organization may preclude modeling a phenomenon such as the **stem-form** in terms of the **stand-closure** and the **site-conditions**. It may not be possible to achieve a simple regression model. There may be stability introduced by the interaction of all levels of factors such that change occurs only after the feed-back mechanisms have broken down; a threshold model with change occurring rapidly after periods of relative stability may be more appropriate.

This study indicates the complexity of an in vivo response to what would be a very simple in vitro phenomenon. A direct response to increased horizontal force on a tapered object would produce stabilization by increased diameter at the base. This does not occur with tree stems. Clearly a simple physiological response at the level of the individual tree is mediated by a number of factors, both deterministic and stochastic. Some of these factors operate at a broader level of influence and some operate at a finer level than the tree stem itself. If natural systems followed a strictly hierarchical structure, the broader influences such as wind force would over-ride the more specific factors such as soil conditions in producing a response in the stem conformation. The result would be a simple model of the **stem-form** entirely predicted

by the **stand-closure**. The response of **stem-form** to changes in **stand-closure** is tempered by **site-conditions**, **elevation** in particular, and by other stochastic/unmeasured factors. The relationship between **stem-form**, **stand-closure** and the **site-conditions** is not a simple, comprehensive hierarchy of influences. The relationship is complex, interactive and not totally predictive with the variables utilized in this study.

7. RECOMMENDATIONS

The application of this study with respect to forest management practices has to be considered within the context of an exploratory analysis without a predictive model. An exact prediction of **stem-form** was not attainable at this point but the importance of stand density and environmental conditions was demonstrated in the growth of the individual tree and the production of timber. The involvement of **elevation** in combination with **stand-closure** in the prediction of **stem-form** indicates the importance of tailoring forestry practices to the environmental conditions that the stand has been growing under.

Significant results were obtained for the **stem-form/stand-closure/site-conditions** relationship for *Pinus contorta*, *Picea mariana*, *Picea engelmannii x glauca*, *Abies lasiocarpa* and *Populus tremuloides*. Expanding the study area and extrapolating the results may assist in providing significant results for *Larix laricina*, *Populus balsamifera* and *Betula papyrifera* but complications will also be introduced in terms of additional information that was not included in the original analysis. The development of a predictive model from this exploratory analysis may involve broadening the study and consideration for the existence of relationships that may not be as straightforward as the original analysis. Even after all possible relationships and combinations of measurable factors have been considered, it may not be possible to establish a predictive model; there are indications that random factors, such as those involved in the stand history and the development of **plant associations** are involved. The inclusion of complex factors and random factors may be somewhat facilitated by

the inclusion of mappable categorical variables through the utilization of geographic information systems.

7.1 Forest Management Practices

The existence of a significant **stem-form/stand-closure/site-conditions** relationship has implications in forest management practices. The diameter at breast height and the total height are the measured parameters that are used to calculate the volume of the individual tree and, ultimately, the amount of merchantable timber that can be harvested from a stand. The relationship between the density of the stand and the taper of the individual trees has been considered in establishing thinning practices. Too dense a stand results in natural thinning and damage to the remaining trees; too open a stand and the individual trees develop a large crown, retain their lower branches and produce a lower quality wood. The involvement of ecological parameters such as **elevation**, as well as **total number of stems**, suggests that reforestation practices should include consideration for these factors in determining the most appropriate levels for restocking. The stem taper increases at higher **elevations**; restocking within the Boreal Uplands and Subalpine Ecoregions at the west end of the study area at a higher **total number of stems** per hectare would partially compensate for this tendency.

Forest cutting practices should include consideration for the amount and type of timber that can be procured from a cut-block based on the expected taper of the trees. High elevation, low density stands produce greater tree taper and more waste in sawlog production. This would suggest that sawmills are best located in areas where the elevations are lower and the stand densities are

higher. The sawmill located in the west end of the study area at Grande Cache utilized timber growing within the Boreal Uplands and Subalpine Ecoregions. It is not well situated in terms of the ecological conditions present; large amounts of chips would be produced relative to the amount of lumber that could be acquired from this area. The projected pulp mill at Whitecourt, on the east side of the study area, would have been equally poorly situated. The lower elevations and high density stands in this area produces trees with little taper. In terms of the most efficient utilization of the timber present, a sawmill would have been best located in this area.

7.2 Limitations

This study was designed to examine the presence or absence of significant relationships; it was not designed to establish a predictive model. In the process of examining the **stem-form/stand-closure/site-conditions** relationship, it was determined that significant relationships could not be established for some of the variables. In particular, there were inconsistencies in the **stem-form/stand-closure** relationship for some species. Significant relationships could not be established for:

1) the **stem-form/stand-closure (total basal area)** relationship for *Larix laricina*, *Populus tremuloides*, *Betula papyrifera* and *Populus balsamifera*

2) the **stem-form/stand-closure (total number of stems)** relationship for *Abies lasiocarpa*, *Larix laricina* and *Betula papyrifera*

3) the **stem-form/site-conditions** relationship for *Larix laricina*

4) the **stem-form/stand-closure/site-conditions** relationship for *Larix laricina*

It may not be possible to establish the role of some **site-conditions** variables in **stem-form** for some species; some species inhabit a limited range of sites. In order to examine whether a broader range of **site-conditions** exists for some species (*Larix laricina*, *Betula papyrifera* and *Populus balsamifera*), sampling would have to be done outside of the study area. Extending the sampling area to achieve a broader range of **site-conditions** must be undertaken with some caution. Certain variables, especially **elevation**, may not be as easily tested in other areas. Elevational influences are confounded by latitude; the effect of increasing latitude parallels the effect of increasing **elevation**. Establishing a relationship between **stem-form** and **elevation** would require adjustment for latitude if a very broad geographic range of sites is being considered.

7.3 Extrapolation

The ultimate test of significance for the relationships established in this study is to extrapolate beyond the study area boundaries and to determine if these relationships are still valid. In so doing, it should be recognized that the application of these results to other study areas may have limitations:

1) other **tree species** which have not been examined may be present
2) the relationship with **elevation** may be complicated by changes in latitude
3) a greater, untested range of variables for **stand-closure** and **site-conditions** may exist outside of the study area
4) significant results for *Larix laricina*, *Betula papyrifera*, *Populus balsamifera* were not obtained

5) there may be an increase in the number of **site-conditions** variables in the relationships with the **stand-closure** and the **stem-form** as the sample size increases

Incorporating other study areas may result in a combination of extending the exploratory nature of the original study where significant results were not obtained and extrapolating the original study where significant results were obtained. It is probable that any rudimentary model developed from the original study would require extensive ratification with the inclusion of other **tree species** and other **site-conditions** and the expansion in the sample size and existing **site-conditions.**

7.4 Modeling

An objective stance was maintained during this study as this was an exploratory analysis. Modeling requires a more deterministic approach and would be the logical next step in exploring the **stem-form/stand-closure/site-conditions** relationship.

The results of this study are restricted to establishing relationships; the result is not a predictive model. The species differences suggest that predictive models would be best built on a species-wise basis. The fairly consistent involvement of **elevation** and the **total number of stems** suggest that a more deterministic approach using forward selection beginning with these two variables would be reasonable. The involvement of other variables varies considerably with the **tree species** involved; this is likely a result of the restricted range of the **site-conditions** occupied by most species. For example, no modeling of *Pinus contorta* on wet sites is possible as it does not have the physiological mechanisms to survive on those sites.

In developing a predictive model, the order of entry of variables makes a great deal of difference unless the independent variables are uncorrelated (Stevens, 1986 pg 65). **Elevation** and the **total number of stems** may be somewhat correlated; germination and stand establishment are likely affected by climatic changes imposed by changes in **elevation**. Where sets of variables are correlated, a linear relationship may be compromised.

The inter-action between variables may lead to either enhancement or negation of the effect of one variable by the presence of another. The effect of the **stand-closure** or of a single **site-conditions** variable may change over its range depending upon its relationship to other variables that may be present. The effect of **stand-closure** on **stem-form** may be complicated more in the denser phases by nutrient levels and more in the open phases by the soil texture. Instead of a linear relationship, a threshold relationship may result.

In terms of the **stem-form/stand-closure/site-conditions** relationship, a threshold would suggest that a diameter increase relative to height would only occur once a critical point in the values for the **site-conditions** plus **stand-closure** was reached. It is also possible that there may be other mechanisms for achieving stability over the short term and there may be a range of tolerance in terms of wind force. Once these mechanisms have broken down, diameter increase occurs rapidly to achieve stability or uprooting occurs if the breakdown of mechanisms occurs too rapidly. A predictive linear relationship may not be achievable.

7.5 Random Factors

The involvement of stochastic factors or random events is difficult to verify. It was not possible to establish that the lack of a statistically significant relationship with the deterministic factors included in this study means that the relationship must therefore be determined by random events; this was not the relationship being tested. However, the selection of **plant associations** in the stepwise regression suggested that stand history may play a part in determining **stand-closure** and **stem-form.**

The **plant associations** utilized in this study were very coarsely defined at a 1:50 000 scale. In less severe climates where the topographic changes are not as dramatic, this level of stratification would not be adequate to describe the vegetation; in this area, the majority of the vegetation was characterized by the transition from pure Pinus contorta on the driest sites through *Pinus contorta* mixed with *Picea mariana* on the moist sites to pure *Picea mariana* on very wet sites. The understory gradient is very similar (Appendix B) with broad changes associated with ecoregional differences. Deviations from this gradient reflected in changes in the understory species composition, the amount of *Populus tremuloides*, *Abies lasiocarpa*, *Picea engelmannii x glauca*, *Populus balsamifera*, *Larix laricina* and *Betula papyrifera* may have been determined by insect and disease infestation, fire, inundation, deposition and the existing vegetation.

7.6 GIS

The categorical variables, **ecoregion**, **plant association** and **soil order**, were included in this analysis despite the probability that there was some multicollinearity with groups of other non-categorical variables. Not only are there random factors included

in the characterization of these variables but indirect information on topographic influences and local climate, plant indicators of soil nutrient status and some consideration for seasonal variation in water conditions can be derived from these categorical variables. In addition, many of these variables are mapped variables; a model utilizing mapped variables may be tied to a physical base utilizing geographic information systems. In this manner, the **stem-form** may potentially be predicted and validated in any given area.

REFERENCES

AGRICULTURE CANADA. 1981. Budd's Flora of the Canadian Prairie Provinces, Research Branch, Publication 1662/1979, Ottawa.

AGRICULTURE CANADA. 1987. Canadian System of Soil Classification, Agriculture Canada Expert Committee on Soil Survey, Agriculture Research Branch, Publication 1646, 2nd edition, Ottawa.

ALBERTA FORESTRY, LANDS and WILDLIFE. 1985. Integrated Resource Inventory Manual Natural Resource Information Services, Resource Evaluation and Planning Division, ENR No. Dept.88, Edmonton.

ALBERTA FORESTRY, LANDS and WILDLIFE. 1988. Integrated Resource Inventory of Fox Creek-Knight Study Area, Land Information Services Division, Publication T/185, Edmonton.

AMATEIS,R.L. and BURKHART,H.E. 1987. Tree Volume and Taper of Loblolly Pine Varies by Stand Origin, Southern Journal of Applied Forestry **11**: 185-189.

AXELSSON,E. and AXELSSON,B. 1986. Changes in Carbon Allocation Patterns in Spruce and Pine Trees Following Irrigation and Fertilization, Tree Physiology **2**: 189-204.

BERENSON,M.L., LEVINE,D.M. and GOLDSTEIN,M. 1983. Intermediate Statistical Methods and Applications, Prentice-Hall Inc., Toronto.

CHILDS,D. 1973. The Essentials of Factor Analysis, Holt, Rinehart and Winston, Toronto.

CLYDE,M.A. and TITUS,S.J. 1987. Radial and Longitudinal Variation in Stem Diameter Increment of Lodgepole Pine, White Spruce and Black Spruce: Species and Crown Class Differences, Canadian Journal of Forestry Research **17**: 1223-1227.

COMEAU,P.G. and KIMMINS,J.P. 1989. Above- and Below-ground Biomass and Production of Lodgepole Pine on Sites With Differing Soil Moisture Regimes, Canadian Journal of Forestry Research **19**: 447-454.

COOK,E.R. and JACOBY,G.C. 1977. Tree Ring-Drought Relationships in the Hudson Valley, New York, Science **198**: 399-401.

CORNS,I.G.W. and ANNAS,R.M. 1984. Ecological Classification of Alberta Forests and its Application for Forest Management in Forest Classification at High Altitudes as an Aid to Regeneration, Proceedings of Fifth International Workshop, General Technical Report Pacific North West Forestry and Range Experimental Station, USDA Forest Service No. DNW-177 55: 40-52.

DANIEL,W.W. 1978. Applied Nonparametric Statistics, Houghton Mifflin Co., Boston.

DAUBENMIRE,R.F. 1946. Radial Growth of Trees at Different Altitudes, Botanical Gazette **107**:462-467.

FARR,W.A., DEMARS,D.J. and DEALY,J.E. 1989. Height and Crown Width Related to Diameter for Open-Grown Western Hemlock and Sitka Spruce, Canadian Journal of Forestry Research **19**: 1203-1207.

FAYLE,D.C.F. 1968. Radial Growth in Tree Roots, Technical Report No.9, Faculty of Forestry, University of Toronto, Toronto.

FISHER,J.B. 1986. Branching Patterns and Angles in Trees in On the Economy of Plant Form and Function, T.J.Givnish ed., Cambridge University Press, New York, 493-523.

GIVNISH,T.J. 1986. Biomechanical Constraints on Crown Geometry in Forest Herbs in On the Economy of Plant Form and Function, T.J.Givnish ed., Cambridge University Press, New York, 525-583.

HALTER,M.R., CHANWAY,C.P. and HARPER,G.J. 1993. Growth Reduction and Root Deformation of Containerized Lodgepole Pine Saplings 11 Years After Planting, Forest Ecology and Management **56**: 131-146.

HORN,H.S. 1971. The Adaptive Geometry of Trees, Princeton University Press.

HOSIE,R.C. 1973. Native Trees of Canada, Information Canada, 7th edition, Ottawa.

HUSCH,B., MILLER,C.I. and BEERS,T.W. 1982. Forest Mensuration, John Wiley & Sons, 3rd edition, Toronto.

JACOBS,M.R. 1954. The Effect of Wind Sway on the Form and Development of *Pinus radiata* D.Don, Australian Journal of Botany **2**: 35-51.

JAQUES BENNETT,K.E. Vegetation Classification of the Berland-Fox Creek Areas, Alberta Forestry, Lands and Wildlife, unpublished.

JOHNSON,E.A. and LARSEN,C.P.S. 1991. Climatically Induced Change in Fire Frequency in the Southern Canadian Rockies, Ecology **72**: 194-201.

KANJI,G.K. 1993. 100 Statistical Tests, Sage Publications, New York.

KING,D.A. 1986. Tree Form, Height Growth, and Susceptibility to Wind Damage in *Acer saccharum*, Ecology **67**: 980-990.

KING,D.A. 1990. The Adaptive Significance of Tree Height, The American Naturalist **135**: 809-828.

KING,D.A. 1991. Tree Allometry, Leaf Size and Adult Tree Size in Old-growth Forests of Western Oregon, Tree Physiology **9**: 369-381.

KING,R.S. and JULSTROM,B. 1982. Applied Statistics Using Computers, Alfred Publishing Co., Palo Alto, CA.

KLEINBAUM, D.G. and KUPPER,L.L. 1978. Applied Regression Analysis and Other Multivariable Methods, Duxbury Press, Boston.

KOCAOGLU,S.S. and JAQUES BENNETT,K.E. 1983. An Integrated Resource Inventory of the Special Lakeland Area Alberta Energy and Natural Resources, ENR Report #T/48, Edmonton.

KOZLOWSKI,T.T. 1962. Tree Growth, The Ronald Press Company, New York.

KOZLOWSKI,T.T., KRAMER,P.J. and PALLARDY,S.G. 1991. The Physiological Ecology of Woody Plants, Academic Press Inc., Toronto.

LI,B., ALLEN,H.L. and McKEAND,S.E. 1991. Nitrogen and Family Effects on Biomass Allocation of Loblolly Pine Seedlings, Forest Science **37**: 271-283.

LINDMAN,H.R. 1992. Analysis of Variance in Experimental Design, Springer-Verlag, New York.

LOEHLE,C. 1986. Phototropism of Whole Trees: Effects of Habitat and Growth Form, The American Midland Naturalist **116**: 190-196.

LOEHLIN,J.C. 1987. Latent Variable Models - An Introduction to Factor, Path, and Structural Analysis, Lawrence Erlbaum Assoc, New Jersey.

LUXMOORE,R.J., KING,A.W. and THARP,M.L. 1991. Approaches to Scaling Up Physiologically Based Soil-Plant Models in Time and Space, Tree Physiology **9**: 281-292.

McMAHON,T.A. 1973. Size and Shape in Biology, Science **179**: 1201-1204.

MILLIKEN,G.A. and JOHNSON,D.E. 1992. Analysis of Messy Data Vol.1, Chapman and Hall, New York.

MILNE,R. 1991. Dynamics of Swaying of *Picea sitchensis*, Tree Physiology **9**: 383-399.

MOSS, E.H. 1983. Flora of Alberta, University of Toronto Press, Toronto.

NEWBERRY,J.D., BURKHART,H.E. and AMATEIS,R.L. 1989. Individual Tree Merchantable Volume to Total Volume Ratios Based on Geometric Solids, Canadian Journal of Forestry Research **19**: 679-683.

PENRIDGE,L.K. and WALKER,J. 1986. The Effect of Neighbouring Trees on Eucalypt Growth in a Semi-arid Woodland in Australia, Journal of Ecology **74**: 925-936.

SALISBURY,F.B. and ROSS,C.W. 1992. Plant Physiology, Wadsworth Inc., Belmont CA.

SCHINDELBECK,R.R. and RIHA,S.J. 1988. Soil Acidity, and the Growth, Biomass Partitioning and Leaf Mineral Composition of Honeylocust (*Gleditsia triacanthos inermis* L.) seedlings, Tree Physiology **4**: 361-369.

SCHULZE,E.-D., KUPPERS,M. and MATYSSEK,R. 1986. The Roles of Carbon Balance and Branching Pattern in the Growth of Woody Species in On the Economy of Plant Form and Function, T.J.Givnish ed., Cambridge University Press, New York, 585-602.

SPRENT,P. 1990. Applied Nonparametric Statistical Methods, Chapman and Hall, New York.

SPSS Inc. 1988. SPSS-X User's Guide , 3rd edition, Chicago.

STENEKER,G.A. 1974. Factors Affecting the Suckering of Trembling Aspen, Forestry Chronicles **50**: 32-34.

STEVENS,J. 1986. Applied Multivariate Statistics for the Social Sciences, Lawrence Erlbaum Associates, New Jersey.

STRONG,W.L. and LEGGATT,K.R. 1981. Ecoregions of Alberta, Alberta Energy and Natural Resources, Resource Evaluation and Planning Division, ENR Tehcnical Report Number T/4, Edmonton.

TABACHNICK,B.G. and FIDELL,L.S. 1989. Using Multivariate Statistics, 2nd edition, Harpur and Row Publishers, New York.

TAKEUCHI,K., YANAI,H. and MUKHERJEE,B. 1982. The Foundation of Multivariate Analysis: A Unified Approach by Means of Projection and Linear Subspaces, Wiley, New York.

TIMELL,T.E. 1986. Compression Wood in Gymnosperms Vol.3, Springer-Verlag, New York.

VERBYLA,D.L. and FISHER,R.F. 1989. An Alternative Approach to Conventional Soil-Site Regression Modeling, Canadian Journal of Forestry Research **19**: 179-184.

WARING,R.H. and PITMAN,G.B. 1985. Modifying Lodgepole Pine Stands to Change Susceptibility to Mountain Pine Beetle Attack, Ecology **66**: 889-897.

WRIGHT,H.A. and BAILEY,A.W. 1982. Fire Ecology, John Wiley & Sons, Toronto.

APPENDICES

APPENDIX A - Plant Association Descriptions

(revised from Jaques Bennett, unpublished)

AW3 - *Populus tremuloides/Rosa spp./Elymus innovatus*

AW4 - *Populus tremuloides/Viburnum edule/Aralia nudicaulis*

BW4 - *Betula papyrifera/Viburnum edule/Aralia nudicaulis*

F7 - *Betula glandulosa/Carex spp./Sphagnum spp.*

M6 - *Salix spp./Carex spp.*

PB4 - *Populus balsamifera/Equisetum spp./Feathermoss*

PL2 - *Pinus contorta/Ledum groenlandicum/Cladina spp.*

PL4 - *Pinus contorta/Feathermoss*

PLAW2 - *Pinus contorta-Populus tremuloides/Arctostaphylos uva-ursi*

PLAW4 - *Pinus contorta-Populus tremuloides/Alnus crispa*

PLFA3 - *Pinus contorta-Abies lasiocarpa/Rhododendron albiflorum/ Cladina spp.*

PLSB4 - *Pinus contorta-Picea mariana/Ledum groenlandicum/ Feathermoss*

SB7 - *Picea mariana/Ledum groenlandicum/Sphagnum spp.*

SBPL6 - *Picea mariana-Pinus contorta/Ledum groenlandicum/ Feathermoss*

SX5 - *Picea engelmannii x glauca/Feathermoss*

SXPL5 - *Picea engelmannii x glauca/Feathermoss*

(H) = species characteristic of high (subalpine) elevations

(M) = species characteristic of mid (uplands/foothills) elevations

(L) = species characteristic of low (mixedwood) elevations

All plant species names according to Moss (1983)

PLANT ASSOCIATION DESCRIPTIONS – AW3

Populus tremuloides/Rosa spp./Elymus innovatus

Status – mature to old, primary successional		
Site – level to sloping topography, dry, warm conditions		
Ecoregion	**Characteristic Species** Latin name	Common name
All	*Populus tremuloides(L.)*	Trembling Aspen
	Picea glauca(L.)	White Spruce
	Rosa spp.	Rose
	Shepherdia canadensis	Canadian Buffalo–berry
	Epilobium angustifolium (M–L.)	Fireweed
	Fragaria virginiana	Wild Strawberry
	Vicia americana(L.)	Wild Vetch
	Lathyrus ochroleucus(L.)	Cream–coloured Vetchling
	Pyrola asarifolia	Common Pink Wintergreen
	Galium boreale	Northern Bedstraw
	Elymus innovatus	Hairy Wild Rye
Montane	*Aster ciliolatus*	Lindley's Aster
Variant	*Aster conspicuous*	Showy Aster
	Thalictrum venulosum	Veiny Meadow Rue
	Delphinium glaucum	Tall Larkspur
Boreal	*Vaccinium myrtilloides(L.)*	Blueberry
Foothills/	*Ledum groenlandicum(M–L.)*	Common Labrador Tea
Boreal	*Lonicera involucrata(L.)*	Bracted Honeysuckle
Mixedwood	*Viburnum edule(L.)*	Low–bush Cranberry
transition	*Cornus canadensis*	Bunchberry
	Maianthemum canadense	Wild Lily–of–the–valley
	Linnaea borealis	Twin–flower
	Rubus pubescens(L.)	Dewberry
	Vaccinium vitis–idaea	Bog Cranberry
	Mertensia paniculata	Tall Mertensia
	Pleurozium schreberi	Schreber's Moss
	Ptilium crista–castrensis	Knight's Plume Moss
	Peltigera canina	Dog Lichen

PLANT ASSOCIATION DESCRIPTIONS – AW4

Populus tremuloides/Viburnum edule/Aralia nudicaulis

Status – mature to old, primary successional		
Site – level to sloping topography, moist to very moist conditions		
Ecoregion	**Characteristic Species** Latin name	Common name
All	*Populus tremuloides(L.)*	Trembling Aspen
	Picea glauca(L.)	White Spruce
	Viburnum edule(L.)	Low–bush Cranberry
	Rosa acicularis	Prickly Rose
	Lonicera involucrata(L.)	Bracted Honeysuckle
	Aralia nudicaulis(L.)	Wild Sarsaparilla
	Cornus canadensis	Bunchberry
	Pyrola asarifolia	Common Pink Wintergreen
	Rubus pubescens(L.)	Dewberry
	Linnaea borealis	Twin–flower
	Epilobium angustifolium(M–L.)	Fireweed
	Petasites palmatus	Palmate–leaved Coltsfoot
	Fragaria virginiana	Wild Strawberry
	Calamagrostis spp.	Marsh Reed Grass
	Lathyrus ochroleucus(L.)	Cream–coloured Vetchling
	Mitella nuda	Bishop's–cap
	Pleurozium schreberi	Schreber's Moss
Boreal Foothills	*Mertensia paniculata*	Tall Mertensia
	Maianthemum canadense	Wild Lily–of–the–valley
	Smilacina racemosa	False Solomon's–seal
	Galium triflorum	Sweet–scented Bedstraw
	Equisetum spp.	Horsetail
	Ptilium crista–castrensis	Knight's Plume Moss
Boreal Mixedwood	*Lycopodium annotinium*	Stiff Club–moss
	Vicia americana(L.)	Wild Vetch

PLANT ASSOCIATION DESCRIPTIONS – BW4

Betula papyrifera/Viburnum edule/Aralia nudicaulis

Status – young to mature, primary successional		
Site –level topography with warm, moist to wet conditions		
Ecoregion	**Characteristic Species** Latin name	Common name
Boreal Mixedwood	*Betula papyrifera(M–L.)*	White Birch
	Picea glauca(L.)	White Spruce
	Viburnum edule(L.)	Low–bush Cranberry
	Lonicera involucrata(L.)	Bracted Honeysuckle
	Rosa acicularis	Prickly Rose
	Ribes lacustre	Bristly Black Currant
	Salix bebbiana(L.)	Beaked Willow
	Rubus idaeus	Wild Red Raspberry
	Aralia nudicaulis(L.)	Wild Sarsaparilla
	Cornus canadensis	Bunchberry
	Linnaea borealis	Twin–flower
	Epilobium angustifolium(M–L.)	Fireweed
	Gymnocarpium dryopteris(L.)	Oak Fern
	Mitella nuda	Bishop's–cap
	Mertensia paniculata	Tall Mertensia
	Equisetum sylvaticum	Woodland Horsetail
	Lycopodium annotinium	Stiff Club–moss
	Rubus pubescens(L.)	Dewberry
	Galium triflorum	Sweet–scented Bedstraw
	Maianthemum canadense	Wild Lily–of–the–valley
	Petasites palmatus	Palmate–leaved Coltsfoot
	Heracleum lanatum	Cow Parsnip
	Aster ciliolatus	Lindey's Aster
	Calamagrostis canadensis	Marsh Reed Grass
	Pleurozium schreberi	Schreber's Moss

PLANT ASSOCIATION DESCRIPTIONS – F7

Betula glandulosa/Carex spp./Sphagnum spp.

Status – mature to old, primary successional		
Site – level to sloping topography, moist to very moist conditions		
Ecoregion	**Characteristic Species** **Latin name**	**Common name**
All	*Picea mariana(M–L.)*	Black Spruce
	Betula glandulosa	Dwarf Birch
	Oxycoccus microcarpus	Small Bog Cranberry
	Carex spp.	Sedge
	Sphagnum spp.	Peat Moss
	Tomenthypnum nitens	Golden Moss
	Aulacomnium palustre	Tufted Moss
Subalpine	*Salix spp.*	Willow
	Equisetum spp.	Horsetail
	Scirpus cespitosus	Tufted Bulrush
Boreal Uplands	*Larix laricina(L.)*	Tamarack
	Ledum groenlandicum(M–L.)	Common Labrador Tea
	Smilacina trifoliata	Three–leaved Solomon's–seal
	Vaccinium vitis–idaea	Bog Cranberry
	Polytricum strictum	Hair Cap Moss
Boreal Foothills	*Larix laricina(L.)*	Tamarack
	Ledum groenlandicum(M–L.)	Ledum groenlandicum
	Salix spp.	Willow
	Smilacina trifoliata	Three–leaved Solomon's–seal
	Vaccinium vitis–idaea	Bog Cranberry
	Polytricum strictum	Hair Cap Moss

PLANT ASSOCIATION DESCRIPTIONS – M6

Salix spp./Carex spp.

Status – young, often treeless, edaphic climax		
Site – level to depressional, wet, subject to flooding and deposition		
Ecoregion	**Characteristic Species** Latin name	Common name
Fluvial	*Betula glandulosa*	Dwarf Birch
	Salix spp.	Willow
	Mertensia paniculata	Tall Mertensia
	Achillea millefolium	Common Yarrow
	Delphinium glaucum	Tall Larkspur
	Valeriana dioica	Northern Valerian
	Stellaria longifolia	Long–leaved Chickweed
	Rubus arcticus	Dwarf Raspberry
	Epilobium angustifolium	Fireweed
	Fragaria virginiana	Wild Strawberry
	Galium boreale	Northern Bedstraw
	Deschampsia cespitosa	Tufted Hair Grass
	Carex spp.	Sedge
	Aulacomnium palustre	Tufted Moss
	Tomenthynum nitens	Golden Moss

PLANT ASSOCIATION DESCRIPTIONS – PB4

Populus balsamifera/Equisetum spp./Feathermoss

Status – mature, primary successional		
Site – level topography, moist to wet conditions, infrequent deposition		
Ecoregion	**Characteristic Species** **Latin name**	**Common name**
Fluvial	*Populus balsamifera(M–L)*	Balsam Poplar
	Populus tremuloides(L.)	Trembling Aspen
	Picea glauca(L.)	White Spruce
	Rosa acicularis	Prickly Rose
	Lonicera involucrata(L.)	Bracted Honeysuckle
	Rubus idaeus	Wild Red Raspberry
	Symphorocarpos albus(L.)	Snowberry
	Ribes spp.	Currant
	Salix bebbiana(L.)	Beaked Willow
	Equisetum spp.	Horsetail
	Rubus pubescens(L.)	Dewberry
	Delphinium glaucum	Tall Larkspur
	Mertensia paniculata	Tall Mertensia
	Cornus canadensis	Bunchberry
	Epilobium angustifolium(M–L.)	Fireweed
	Maianthemum canadense	Wild Lily–of–the–valley
	Thalictrum venulosum	Veiny Meadow Rue
	Fragaria virginiana	Wild Strawberry
	Galium boreale	Northern Bedstraw
	Petasites palmatus	Palmate–leaved Coltsfoot
	Lathyrus ochroleucus(L.)	Cream–coloured Vetchling
	Mitella nuda	Bishop's–cap
	Vicia americana	Wild Vetch
	Aster ciliolatus	Lindley's Aster
	Heracleum lanatum	Cow Parsnip
	Achillea millefolium	Common Yarrow

PLANT ASSOCIATION DESCRIPTIONS – PL2

Pinus contorta/Ledum groenlandicum/Cladina spp.

Status – young to mature, primary successional, edaphic climax		
Site – level to gently sloping topography, very dry conditions		
Ecoregion	**Characteristic Species** **Latin name**	**Common name**
All	*Pinus contorta (M)*	Lodgepole Pine
	Ledum groenlandicum(M–L)	Common Labrador Tea
	Vaccinium myrtilloides(L)	Blueberry
	Vaccinium vitis–idaea	Bog Cranberry
	Cladina/Cladonia spp.	Reindeer Lichen
	Peltigera spp.	
Subalpine/	*Vaccinium membranaceum(H)*	Tall Bilberry
Boreal	*Empetrum nigrum(H)*	Crowberry
Uplands	*Vaccinium caespitosum(M)*	Dwarf Bilberry
transition	*Lycopodium clavatum*	Common Club–moss
	Pyrola chlorantha	Greenish–flowered Wintergreen
	Pleurozium schreberi	Schreber's Moss
	Ptilium crista–castrensis	Knight's Plume Moss
Boreal	*Vaccinium caespitosum(M)*	Dwarf Bilberry
Uplands	*Arctostaphylos uva–ursi*	Bearberry
	Linnaea borealis	Twin–flower
	Pleurozium schreberi	Schreber's Moss
	Dicranum polysetum	Cushion Moss
	Hylocomium splendens	Stair–step Moss
	Stereocaulon tomentosum	
Boreal	*Rosa acicularis*	Prickly Rose
Foothills	*Vaccinium caespitosum(M)*	Dwarf Bilberry
	Linnaea borealis	Twin–flower
	Elymus innovatus	Hairy Wild Rye
	Pleurozium schreberi	Schreber's Moss
	Hylocomium splendens	Stair–step Moss
	Ptilium crista–castrensis	Knight's Plume Moss
	Polytricum juniperinum	Hair–cap Moss
Boreal	*Rosa acicularis*	Prickly Rose
Mixedwood	*Epilobium angustifolium(M–L)*	Fireweed
	Linnaea borealis	Twin–flower

PLANT ASSOCIATION DESCRIPTIONS – PL4

Pinus contorta/Feathermoss

Status – mature to old, primary successional		
Site – level to sloping topography, moist to very moist conditions		
Ecoregion	**Characteristic Species** Latin name	Common name
All	*Pinus contorta(M)*	Lodgepole Pine
	Abies lasiocarpa(H–M)	Subalpine Fir
	Rubus pedatus(H)	Five–leaved Bramble
	Cornus canadensis	Bunchberry
	Lycopodium annotinium	Stiff Club–moss
	Pleurozium schreberi	Schreber's Moss
	Ptilium crista–castrensis	Knight's Plume Moss
	Hylocomium splendens	Stair–step Moss
	Peltigera aphthosa	Studded Leather Lichen
Subalpine	*Rhododendron albiflorum(H)*	White–flowered Rhododendron
	Ledum groenlandicum(M–L)	Common Labrador Tea
	Menziesia ferruginea(H)	False–azalea
	Vaccinium membranaceum(H)	Tall Bilberry
	Vaccinium vitis–idaea	Bog Cranberry
Boreal	*Streptopus amplexifolius*	Twisted–stalk
Uplands	*Streptopus roseus*	Twisted–stalk
	Petasites palmatus	Palmate–leaved Coltsfoot
	Orthilia secunda	One–sided Wintergreen
	Pyrola asarifolia	Common Pink Wintergreen
	Arnica cordifolia(H)	Heart–leaved Arnica
	Rubus pubescens(L)	Dewberry
	Epilobium angustifolium(M–L)	Fireweed
	Mertensia paniculata	Tall Mertensia
	Equisetum spp.	Horsetail
	Calamagrostis spp.	Marsh Reed Grass
	Dicranum fuscescens	Cushion Moss

PLANT ASSOCIATION DESCRIPTIONS – PLAW2

Pinus contorta–Populus tremuloides/Arctostaphylos uva–ursi

Status – young to mature, primary successional		
Site – steep, warm, very dry slopes (Smoky Valley)		
Ecoregion	**Characteristic Species** **Latin name**	**Common name**
Montane	*Pinus contorta(M)*	Lodgepole Pine
Variant	*Populus tremuloides(L)*	Trembling Aspen
	Picea engelmannii x glauca(M)	Engelmann x White Spruce
	Salix spp.	Willow
	Arctostaphylos uva–ursi	Bearberry
	Achillea millefolium	Common Yarrow
	Cornus canadensis	Bunchberry
	Epilobium angustifolium(M–L)	Fireweed
	Castilleja spp.	Paint–brush
	Gentianella amarella	Felwort
	Elymus innovatus	Hairy Wild Rye
	Peltigera malacea	
	Cladina/Cladonia spp.	Reindeer Lichen

PLANT ASSOCIATION DESCRIPTIONS – PLAW4

Pinus contorta–Populus tremuloides/Alnus crispa

Status –mature, primary successional		
Site – level to sloping, subsurface seepage, moist conditions		
Ecoregion	**Characteristic Species** Latin name	Common name
All	*Pinus contorta(M)*	Lodgepole Pine
	Alnus crispa(M)	Green Alder
	Rosa acicularis	Prickly Rose
	Cornus canadensis	Bunchberry
	Arnica cordifolia(H)	Heart–leaved Arnica
	Epilobium angustifolium(M–L)	Fireweed
	Linnaea borealis	Twin–flower
	Mertensia paniculata	Tall Mertensia
	Calamagrostis spp.	Marsh Reed Grass
	Pleurozium schreberi	Schreber's Moss
	Ptilium crista–castrensis	Knight's Plume Moss
Boreal Foothills	*Populus tremuloides(L)*	Trembling Aspen
	Lonicera involucrata(L)	Bracted Honeysuckle
	Ribes lacustre	Bristly Black Currant
	Sorbus scopulina(M–L)	Mountain Ash
	Vaccinium myrtilloides(L)	Blueberry
	Viburnum edule(L)	Low–bush Cranberry
	Rubus pubescens(L)	Dewberry
	Petasites palmatus	Palmate–leaved Coltsfoot
	Pyrola asarifolia	Common Pink Wintergreen
	Lycopodium annotinium	Stiff Club–moss
	Gymnocarpium dryopteris(L)	Oak Fern
	Hylocomium splendens	Stair–step Moss
Boreal Uplands/ Boreal Foothills transition	*Populus tremuloides(L)*	Trembling Aspen
	Vaccinium myrtilloides(L)	Blueberry
	Viburnum edule(L)	Low–bush Cranberry
	Maianthemum canadense	Wild Lily–of–the–valley
	Rubus pubescens(L)	Dewberry
	Pyrola asarifolia	Common Pink Wintergreen
	Lycopodium annotinium	Stiff Club–moss
Subalpine/ Boreal Uplands transition	no distinct species	

PLANT ASSOCIATION DESCRIPTIONS – PLFA3

Pinus contorta–Abies lasiocarpa/Rhododendron albiflorum/Cladina spp.

Status – mature, primary successional, transition to climax		
Site – sloping, dry conditions, thin soil, bedrock close to surface		
Ecoregion	**Characteristic Species** Latin name	Common name
Subalpine	*Pinus contorta(M)*	Lodgepole Pine
	Abies lasiocarpa(H–M)	Subalpine Fir
	Rhododendron albiflorum(H)	White–flowered Rhododendron
	Menziesia ferruginea(H)	False–azalea
	Vaccinium membranaceum(H)	Tall Bilberry
	Ledum groenlandicum(M–L)	Common Labrador Tea
	Salix scouleriana(M–L)	Scouler's Willow
	Cornus canadensis	Bunchberry
	Empetrum nigrum(H)	Crowberry
	Rubus pedatus(H)	Five–leaved Bramble
	Vaccinium vitis–idaea	Bog Cranberry
	Pleurozium schreberi	Schreber's Moss
	Pohlia nutans	Copper Wire Moss
	Polytrichum juniperinum	Hair Cap Moss
	Hylocomium splendens	Stair–step Moss
	Dicranum scoparium	Broom Moss
	Ptilium crista–castrensis	Knight's Plume Moss
	Dicranum fuscescens	Cushion Moss
	Cladonia/Cladina spp.	Reindeer Moss
	Peltigera aphthosa	Studded Leather Lichen
	Stereocaulon tomentosum	

PLANT ASSOCIATION DESCRIPTIONS – PLSB4

Pinus contorta–Picea mariana/Ledum groenlandicum/Feathermoss

Status – mature, primary successional, transition to climax		
Site – level to gently sloping, moist conditions		
Ecoregion	**Characteristic Species** Latin name	Common name
All	*Pinus contorta(M)*	Lodgepole Pine
	Picea mariana(M–L)	Black Spruce
	Ledum groenlandicum(M–L)	Common Labrador Tea
	Vaccinium vitis–idaea	Bog Cranberry
	Cornus canadensis	Bunchberry
	Linnaea borealis	Twin–flower
	Pleurozium schreberi	Schreber's Moss
	Hylocomium splendens	Stair–step Moss
	Ptilium crista–castrensis	Knight's Plume Moss
	Cladina/Cladonia spp.	Reindeer Lichen
	Peltigera aphthosa	Studded Leather Lichen
Subalpine/ Boreal Uplands transition	*Vaccinium membranaceum(H)*	Tall Bilberry
	Rubus pedatus(H)	Five–leaved Bilberry
	Vaccinium caespitosum(M)	Dwarf Bilberry
	Polytricum juniperinum	Hair Cap Moss
Boreal Uplands	*Vaccinium myrtilloides(L)*	Blueberry
	Lycopodium annotinium	Stiff Club–moss
Boreal Uplands/ Boreal Foothills transition	*Populus tremuloides(L)*	Trembling Aspen
	Picea glauca(L)	White Spruce
	Alnus crispa(M)	Green Alder
	Vaccinium myrtilloides(L)	Blueberry
	Rosa acicularis	Prickly Rose
	Viburnum edule(L)	Low–bush Cranberry
	Vaccinium membranaceum(H)	Tall Bilberry
	Epilobium angustifolium(M–L)	Fireweed
	Vaccinium caespitosum(M)	Dwarf Bilberry
	Petasites palmatus	Palmate–leaved Coltsfoot
	Rubus pubescens(L)	Dewberry
	Arnica cordifolia(H)	Heart–leaved Arnica
	Lycopodium complanatum	Ground Cedar
	Pyrola asarifolia	Common Pink Wintergreen
	Orthilia secunda	One–sided Wintergreen
	Calamagrostis canadensis	Marsh Reed Grass
	Dicranum polysetum	Cushion Moss
	Dicranum fuscescens	Cushion Moss
	Ptilidium pulcherrimum	Liverwort

PLANT ASSOCIATION DESCRIPTIONS – PLSB4 CONTINUED

Pinus contorta–Picea mariana/Ledum groenlandicum/Feathermoss

Ecoregion	Characteristic Species Latin name	Common name
Boreal	*Rosa acicularis*	Prickly Rose
Foothills	*Vaccinium myrtilloides(L.)*	Blueberry
	Lycopodium annotinium	Stiff Club–moss
	Petasites palmatus	Palmate–leaved Coltsfoot
	Epilobium angustifolium(M–L.)	Fireweed
	Calamagrostis canadensis	Marsh Reed Grass
Boreal	*Vaccinium myrtilloides(L.)*	Blueberry
Mixedwood	*Abies lasiocarpa(H–M)*	Subalpine Fir
	Epilobium angustifolium(M–L.)	Fireweed
	Petasites palmatus	Palmate–leaved Coltsfoot
	Maianthemum candense	Wild Lily–of–the–valley

PLANT ASSOCIATION DESCRIPTIONS – SB7

Picea mariana/Ledum groenlandicum/Sphagnum spp.

Status – mature to old, edaphic climax		
Site – depressional, wet conditions		
Ecoregion	**Characteristic Species** **Latin name**	**Common name**
All	*Picea mariana(M–L.)*	Black Spruce
	Salix spp.	Willow
	Ledum groenlandicum(M–L.)	Common Labrador Tea
	Vaccinium vitis–idaea	Bog Cranberry
	Rubus chamaemorus	Cloudberry
	Smilacina trifolia	Three–leaved Solomon's–seal
	Equisetum spp.	Horsetail
	Carex spp.	Sedge
	Pleurozium schreberi	Schreber's Moss
	Sphagnum spp.	Peat Moss
	Aulacomnium palustre	Tufted Moss
Boreal Uplands	*Oxycoccus microcarpus*	Small Bog Cranberry
	Hylocomium splendens	Stair–step Moss
	Tomenthypnum nitens	Golden Moss
Boreal Foothills	*Cornus canadensis*	Bunchberry
	borealis	Twin–flower
	Calamagrostis canadensis	Marsh Reed Grass
	Hylocomium splendens	Stair–step Moss
	Ptilium crista–castrensis	Knight's Plume Moss
	Cladina/Cladonia spp.	Reindeer Moss
	Peltigera aphthosa	Studded Leather Lichen
Boreal Mixedwood	*Oxycoccus microcarpus*	Small Bog Cranberry
	Calamagrostis canadensis	Marsh Reed Grass
	Cladina/Cladonia spp.	Reindeer Lichen

PLANT ASSOCIATION DESCRIPTIONS – SBPL6

Picea mariana–Pinus contorta/Ledum groenlandicum/Feathermoss

Status – mature to old, primary successional, transition to climax		
Site – level to depressional, moist to wet conditions		
Ecoregion	**Characteristic Species** **Latin name**	**Common name**
All	*Picea mariana(M–L)*	Black Spruce
	Pinus contorta(M)	Lodgepole Pine
	Ledum groenlandicum(M–L)	Common Labrador Tea
	Vaccinium vitis–idaea	Bog Cranberry
	Cornus canadensis	Bunchberry
	Linnaea borealis	Twin–flower
	Pleurozium schreberi	Schreber's Moss
	Hylocomium splendens	Stair–step Moss
	Ptilium crista–castrensis	Knight's Plume Moss
	Cladina/Cladonia spp.	Reindeer Lichen
	Peltigera aphthosa	Studded Leather Lichen
Subalpine/	*Abies lasiocarpa(H–M)*	Subalpine Fir
Boreal	*Vaccinium membranaceum(H)*	Tall Bilberry
Uplands	*Empetrum nigrum(H)*	Crowberry
transition	*Vaccinium caespitosum(M)*	Dwarf Bilberry
	Dicranum scoparium	Broom Moss
Boreal	*Vaccinium myrtilloides(L)*	Blueberry
Uplands	*Vaccinium caespitosum(M)*	Dwarf Bilberry
	Petasites palmatus	Palmate–leaved Coltsfoot
Boreal	*Rosa acicularis*	Prickly Rose
Foothills	*Equisetum spp.*	Horsetail
	Petasites palmatus	Palmate–leaved Coltsfoot
	Dicranum spp.	Cushion Moss

PLANT ASSOCIATION DESCRIPTIONS – SX5

Picea engelannii x glauca/Feathermoss

Status – mature to old, climax		
Site – level to sloping topography, moist to very moist conditions		
Ecoregion	**Characteristic Species** **Latin name**	**Common name**
All	*Picea engelmannii x glauca(M)*	White x Engelmann Spruce
	Lonicera spp.(M)	Honeysuckle
	Equisetum spp.	Horsetail
	Mitella nuda	Bishop's–cap
	Petasites palmatus	Palmate–leaved Colts–foot
	Mertensia paniculata	Tall Mertensia
	Hylocomium splendens	Stair–step Moss
	Pleurozium schreberi	Schreber's Moss
	Ptilium crista–castrensis	Knight's Plume Moss
Subalpine	*Ribes lacustre*	Bristly Black Currant
	Cornus canadensis	Bunchberry
	Arnica cordifolia(H)	Heart–leaved Arnica
	Dicranum spp.	Cushion Moss
	Peltigera aphthosa	Studded Leather Lichen
Boreal Uplands	*Abies lasiocarpa(H–M)*	Subalpine Fir
	Pinus contorta(M)	Lodgepole Pine
	Viburnum edule(L)	Low–bush Cranberry
	Rosa acicularis	Prickly Rose
	Ribes lacustre	Bristly Black Currant
	Cornus canadensis	Bunchberry
	Streptopus amplexifolius	Twisted–stalk
	Linnaea borealis	Twin–flower
	Arnica cordifolia(H)	Heart–leaved Arnica
	Rubus pedatus(H)	Five–leaved Bramble
	Lycopodium annotinium	Stiff Club–moss
	Orthilia secunda	One–sided Wintergreen
	Pyrola asarifolia	Common Pink Wintergreen
	Dicranum fuscescens	Cushion Moss
	Peltigera aphthosa	Studded Leather Lichen
	Cladina/Cladonia spp.	Reindeer Lichen

Picea engelannii x glauca/Feathermoss

Ecoregion	Characteristic Species Latin name	Common name
Boreal	*Abies lasiocarpa(H–M)*	Subalpine Fir
Foothills	*Viburnum edule(L.)*	Low–bush Cranberry
	Rosa acicularis	Prickly Rose
	Sorbus scopulina(M–L.)	Mountain Ash
	Ribes lacustre	Bristly Black Currant
	Cornus canadensis	Bunchberry
	Linnaea borealis	Twin–flower
	Rubus pubescens(L.)	Dewberry
	Streptopus amplexifolius	Twisted–stalk
	Delphinium glauca	Tall Larkspur
	Smilacina racemosa	False Solomon's–seal
	Maianthemum candense	Wild Lily–of–the–valley
	Pyrola asarifolia	Common Pink Wintergreen
	Gymnocarpium dryopteris(L.)	Oak Fern
	Epilobium angustifolium(M–L.)	Fireweed
	Fragaria virginiana	Wild Strawberry
	Galium triflorum	Sweet–scented Bedstraw
	Calamagrostis canadensis	Marsh Reed Grass
Boreal	*Abies lasiocarpa(H–M)*	Subalpine Fir
Mixedwood	*Ribes lacustre*	Bristly Black Currant
	Rosa acicularis	Prickly Rose
	Viburnum edule(L.)	Low–bush Cranberry
	Cornus canadensis	Bunchberry
	Linnaea borealis	Twin–flower
	Achillea millefolium	Common Yarrow
	Aralia nudicaulis(L.)	Wild Sarsaparilla
	Rubus pubescens(L.)	Dewberry
	Galium triflorum	Sweet–scented Bedstraw
	Aster ciliolatus	Lindley's Aster
	Galium boreale	Northern Bedstraw
	Goodyera repens	Rattlesnake Orchid
	Calamagrostis canadensis	Marsh Reed Grass
Fluvial	*Rosa acicularis*	Prickly Rose
	Fragaria virginiana	Wild Strawberry
	Epilobium angustifolium(M–L.)	Fireweed
	Linnaea borealis	Twin–flower
	Peltigera aphthosa	Studded Leather Lichen

PLANT ASSOCIATION DESCRIPTIONS – SXPL5

Picea engelmannii x glauca/Feathermoss

Status – mature to old, primary successional, transition to climax		
Site – variable, moist to very moist		
Ecoregion	**Characteristic Species** **Latin name**	**Common name**
	Picea engelmannii x glauca(M)	Engelmann x White Spruce
	Pinus contorta(M)	Lodgepole Pine
	Abies lasiocarpa(H–M)	Subalpine Fir
	Linnaea borealis	Twin–flower
	Lycopodium annotinium	Stiff Club–moss
	Streptopus amplexifolius	Twisted–stalk
	Pleurozium schreberi	Schreber's Moss
	Ptilium crista–castrensis	Knight's Plume Moss
	Hylocomium splendens	Stair–step Moss
Subalpine	*Vaccinium membranaceum(H)*	Tall Bilberry
	Rhododendron albiflorum(H)	White–flowered Rhododendron
	Menziesia ferruginea(H)	False–azalea
	Ledum groenlandicum(M)	Common Labrador Tea
	Rubus pedatus(H)	Five–leaved Bramble
	Cornus canadensis	Bunchberry
	Orthilia secunda	One–sided Wintergreen
	Arnica cordifolia(H)	Heart–leaved Arnica
	Vaccinium vitis–idaea	Bog Cranberry
	Peltigera aphthosa	Studded Leather Lichen
Foothills	*Betula papyrifera(M)*	White Birch
	Oplopanax horridum(L)	Devil's Club
	Lonicera involucrata(L)	Bracted Honeysuckle
	Viburnum edule(L)	Low–bush Cranberry
	Rosa acicularis	Prickly Rose
	Ribes lacustre	Bristly Black Currant
	Sorbus scopulina(M–L)	Mountain Ash
	Rubus idaeus	Wild Red Raspberry
	Gymnocarpium dryopteris(L)	Oak Fern
	Rubus pubescens(L)	Dewberry
	Mitella nuda	Bishop's–cap
	Pyrola asarifolia	Common Pink Wintergreen
	Maianthemum canadense	Wild Lily–of–the–valley
	Mertensia paniculata	Tall Mertensia
	Petasites palmatus	Palmate–leaved Coltsfoot
	Smilicina racemosa	False Solomon's–seal
	Equisetum spp.	Horsetail
	Tiarella spp.	Foamflower
	Calamagrostis canadensis	Marsh Reed Grass
	Dicranum fuscescens	Cushion Moss

APPENDIX B - Partial Correlation Coefficients for Final Regressions

Stand-closure - **Total Basal Area** with Macro, Meso and Micro Variables

- Log base 10 **Total Number of Stems** with Macro, Meso and Micro Variables

Stem-form - Log base 10 **Stem-form** with Macro, Meso and Micro Variables

- Log base 10 **Stem-form** with **Stand-closure** (**Total Basal Area**, Log base 10 **Total Number of Stems**), Macro, Meso and Micro Variables

PARTIAL CORRELATION COEFFICIENTS
STAND–CLOSURE (TBA) and MACRO SITE–CONDITIONS
TOTAL BASAL AREA (TBA)
MACRO SITE–CONDITIONS
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	TBA MONTANE p=	TBA SUBALPINE p=	TBA BOREAL UPLAND p=	TBA BOREAL FOOTHILLS p=	TBA BOREAL MIXEDWD p=	TBA FLUVIAL p=	TBA SOUTH EFFECT p=	TBA WEST EFFECT p=	TBA ELEVATION p=
Pinus contorta	−0.221	−0.251		0.208	−0.155				
Picea mariana	n/d			0.492					
Picea engelmannii 'x' glauca	−0.491		−0.255				0.439	−0.225	−0.524
Abies lasiocarpa	n/d	−0.806		−0.363	n/d				
Larix laricina	n/d	n/d	n/d			n/d			
Populus tremuloides		n/d			−0.500			−0.316	
Betula papyrifera	n/d	n/d	n/d					−0.995	
Populus balsamifera		−0.998						−0.847	
All–species	0.100	−0.264	−0.202		−0.157				

+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS

STAND–CLOSURE (TBA) and MESO SITE–CONDITIONS

TOTAL BASAL AREA (TBA)

MESO SITE–CONDITIONS

PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	TBA STEMS FM1 SQRT p=	TBA STEMS FM2 SQRT p=	TBA STEMS FM3 SQRT p=	TBA STEMS FM4 SQRT p=	TBA DEAD STEMS SQRT p=	TBA DBH AGE SQRT p=
Pinus contorta	0.128+	0.186				0.254
Picea mariana						0.534
Picea engelmannii 'x' glauca						
Abies lasiocarpa	0.624		n/d			
Larix laricina	n/d			n/d		0.970
Populus tremuloides		0.459	n/d		0.375	0.274
Betula papyrifera			n/d			−0.935
Populus balsamifera	0.997		n/d		0.961	
All–species	0.202	0.270		0.241	0.136	0.209

+ r is not significantly different from 0.000 (alpha=.05/2)

'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations

n/d no data for this species for this variable

empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STAND–CLOSURE (TBA) and MICRO SITE–CONDITIONS

TOTAL BASAL AREA (TBA)
MICRO SITE–CONDITIONS
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	TBA MINERAL p=	TBA WETLAND p=	TBA WOOD p=	TBA SOLUM THICKNESS p=	TBA pH p=	TBA TEXTURE p=	TBA DRAINAGE p=
Pinus contorta		−.124+	0.339				
Picea mariana	n/d						
Picea engelmannii 'x' glauca	n/d				0.208+		0.225
Abies lasiocarpa	n/d	n/d					0.550
Larix laricina	n/d						
Populus tremuloides	n/d	n/d				−0.335	
Betula papyrifera	n/d	n/d	−0.777			−0.950	
Populus balsamifera	n/d	n/d		0.902		−0.996	0.994
All–species		−0.156	0.142	−0.122			0.084+

+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STAND–CLOSURE (TBA) and MICRO SITE–CONDITIONS continued
TOTAL BASAL AREA (TBA)
MICRO SITE–CONDITIONS
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	TBA REGOSOL p=	TBA BRUNISOL p=	TBA LUVISOL p=	TBA GLEYSOL p=	TBA ORGANIC p=
Pinus contorta					n/d
Picea mariana					
Picea engelmannii 'x' glauca				−0.314	
Abies lasiocarpa	n/d				n/d
Larix laricina	n/d	n/d	n/d		
Populus tremuloides					n/d
Betula papyrifera	n/d				n/d
Populus balsamifera			−0.898	0.993	n/d
All–species	−0.143			−0.126	

\+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STAND–CLOSURE (TBA) and PLANT ASSOCIATION
TOTAL BASAL AREA (TBA)
PLANT ASSOCIATION
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	TBA AW3 p=	TBA AW4 p=	TBA BW4 p=	TBA PB4 p=	TBA PLAW2 p=	TBA PLAW4 p=	TBA PLFA3 p=	TBA PL4 p=
Pinus contorta		n/d	n/d	n/d			−0.205	0.213
Picea mariana	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
Picea engelmannii 'x' glauca	−0.234		n/d				n/d	
Abies lasiocarpa	n/d	n/d	n/d	n/d	n/d			0.743
Larix laricina	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
Populus tremuloides		0.336					n/d	n/d
Betula papyrifera	n/d				n/d	n/d	n/d	n/d
Populus balsamifera		0.997	−0.999		−0.991		n/d	n/d
All–species	−0.145		−0.235		−0.303		−0.235	

+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STAND–CLOSURE (TBA) and PLANT ASSOCIATION continued
TOTAL BASAL AREA (TBA)
PLANT ASSOCIATION
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	TBA PL2 p=	TBA PLSB4 p=	TBA SBPL6 p=	TBA SB7 p=	TBA SX5 p=	TBA SXPL5 p=	TBA M6 p=
Pinus contorta	−0.252						
Picea mariana		0.544				n/d	
Picea engelmannii 'x' glauca	n/d		−0.290	n/d			−0.287
Abies lasiocarpa	n/d	n/d		n/d		0.477	n/d
Larix laricina	n/d		n/d		n/d	n/d	n/d
Populus tremuloides	n/d		n/d	n/d		−0.284	n/d
Betula papyrifera	n/d		n/d	n/d		n/d	n/d
Populus balsamifera	n/d	n/d	n/d	n/d		n/d	n/d
All–species	−0.221		−0.261	−0.254		−0.204	−0.159

+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STAND–CLOSURE (TNS) and MACRO SITE–CONDITIONS
LOG base 10 TOTAL NUMBER OF STEMS (TNSLOG)
MACRO SITE–CONDITIONS
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	TNSLOG MONTANE p=	TNSLOG SUBALPINE p=	TNSLOG BOREAL UPLAND p=	TNSLOG BOREAL FOOTHILLS p=	TNSLOG BOREAL MIXEDWD p=	TNSLOG FLUVIAL p=	TNSLOG SOUTH EFFECT p=	TNSLOG WEST EFFECT p=	TNSLOG ELEVATION p=
Pinus contorta						−0.180	−0.186		0.225
Picea mariana	n/d			0.299					
Picea engelmannii 'x' glauca	−0.239			−0.420					
Abies lasiocarpa	n/d				n/d		0.342		
Larix laricina	n/d	n/d	n/d			n/d			−1.000 F undef
Populus tremuloides		n/d		−0.421			0.483	−0.499	
Betula papyrifera	n/d	n/d	n/d					−1.000 F undef	
Populus balsamifera				−0.860	0.824				
All–species	0.228	0.138							

\+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at
lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STAND–CLOSURE (TNS) and MESO SITE–CONDITIONS
LOG base 10 TOTAL NUMBER OF STEMS (TNSLOG)
MESO SITE–CONDITIONS
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	TNSLOG STEMS FM1 SQRT p=	TNSLOG STEMS FM2 SQRT p=	TNSLOG STEMS FM3 SQRT p=	TNSLOG STEMS FM4 SQRT p=	TNSLOG DEAD STEM SQRT p=	TNSLOG DBH AGE SQRT p=
Pinus contorta	−0.188			−0.343	0.145	−0.131+
Picea mariana						
Picea engelmannii 'x' glauca	−0.322					−0.292
Abies lasiocarpa			n/d			−0.373
Larix laricina	n/d			n/d		
Populus tremuloides			n/d		0.564	−0.350
Betula papyrifera		1.000 F undef	n/d			
Populus balsamifera			n/d		0.960	
All–species	−0.191		0.105		0.190	−0.164

+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STAND–CLOSURE (TNS) and MICRO SITE–CONDITIONS
LOG base 10 TOTAL NUMBER OF STEMS (TNSLOG)
MICRO SITE–CONDITIONS
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	TNSLOG MINERAL p=	TNSLOG WETLAND p=	TNSLOG WOOD p=	TNSLOG SOLUM THICKNESS p=	TNSLOG pH p=	TNSLOG TEXTURE p=	TNSLOG DRAINAGE p=
Pinus contorta	−0.176			0.134+			
Picea mariana	n/d	−0.373					
Picea engelmannii 'x' glauca	n/d	−0.265		0.283	−0.272		0.507
Abies lasiocarpa	n/d	n/d	−0.500				0.705
Larix laricina	n/d					1.000 F undef	
Populus tremuloides	n/d	n/d					0.308
Betula papyrifera	n/d	n/d			1.000 F undef		1.000 F undef
Populus balsamifera	n/d	n/d					0.463+
All–species		−0.145			−0.124		0.140

\+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STAND–CLOSURE (TNS) and MICRO SITE–CONDITIONS continued
LOG base 10 TOTAL NUMBER OF STEMS (TNSLOG)
MICRO SITE–CONDITIONS
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	TNSLOG REGOSOL p=	TNSLOG BRUNISOL p=	TNSLOG LUVISOL p=	TNSLOG GLEYSOL p=	TNSLOG ORGANIC p=
Pinus contorta					n/d
Picea mariana					
Picea engelmannii 'x' glauca		0.226			0.477
Abies lasiocarpa	n/d				n/d
Larix laricina	n/d	n/d	n/d		
Populus tremuloides					n/d
Betula papyrifera	n/d		1.000 F undef		n/d
Populus balsamifera			−0.6‡2		n/d
All–species					

+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STAND–CLOSURE (TNS) and PLANT ASSOCIATION
LOG base 10 TOTAL NUMBER OF STEMS (TNSLOG)
PLANT ASSOCIATION
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	TNSLOG AW3 p=	TNSLOG AW4 p=	TNSLOG BW4 p=	TNSLOG PB4 p=	TNSLOG PLAW2 p=	TNSLOG PLAW4 p=	TNSLOG PLFA3 p=	TNSLOG PL4 p=
Pinus contorta		n/d	n/d	n/d		−0.222	−0.307	
Picea mariana	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
Picea engelmannii 'x' glauca			n/d				n/d	
Abies lasiocarpa	n/d	n/d	n/d	n/d	n/d			0.731
Larix laricina	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
Populus tremuloides		−0.267					n/d	n/d
Betula papyrifera	n/d	−1.000 F undef			n/d	n/d	n/d	n/d
Populus balsamifera					n/d		n/d	n/d
All–species	−0.122				−0.249			0.296

\+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STAND–CLOSURE (TNS) and PLANT ASSOCIATION continued
LOG base 10 TOTAL NUMBER OF STEMS (TNSLOG)
PLANT ASSOCIATION
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	TNSLOG PL2 p=	TNSLOG PLSB4 p=	TNSLOG SBPL6 p=	TNSLOG SB7 p=	TNSLOG SX5 p=	TNSLOG SXPL5 p=	TNSLOG M6 p=
Pinus contorta					−0.249	−0.316	
Picea mariana	−0.419					n/d	
Picea engelmannii 'x' glauca	n/d		−0.283	n/d			
Abies lasiocarpa	n/d	n/d		n/d			n/d
Larix laricina	n/d		n/d	−1.000 F undef	n/d	n/d	n/d
Populus tremuloides	n/d		n/d	n/d			n/d
Betula papyrifera	n/d		n/d	n/d		n/d	n/d
Populus balsamifera	n/d	n/d	n/d	n/d		n/d	n/d
All–species	0.256	0.339	0.326	0.225			

+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STEM–FORM and MACRO SITE–CONDITIONS
LOG base 10 STEM–FORM (STFORMLG)
MACRO SITE–CONDITIONS
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	STFORMLG MONTANE p=	STFORMLG SUBALPINE p=	STFORMLG BOREAL UPLAND p=	STFORMLG BOREAL FOOTHILLS p=	STFORMLG BOREAL MIXEDWD p=	STFORMLG FLUVIAL p=	STFORMLG SOUTH EFFECT p=	STFORMLG WEST EFFECT p=	STFORMLG ELEVATION p=
Pinus contorta	0.193			0.158	0.230				0.332
Picea mariana	n/d								0.616
Picea engelmannii 'x' glauca			0.199+						0.313
Abies lasiocarpa	n/d				n/d				0.468
Larix laricina	n/d	n/d	n/d			n/d			
Populus tremuloides		n/d		0.304					
Betula papyrifera	n/d	n/d	n/d						
Populus balsamifera				0.591					
All–species	−0.206								0.312

+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STEM–FORM and MESO SITE–CONDITIONS
LOG base 10 STEM–FORM (STFORMLG)
MESO SITE–CONDITIONS
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	STFORMLG STEMS FM1 SQRT p=	STFORMLG STEMS FM2 SQRT p=	STFORMLG STEMS FM3 SQRT p=	STFORMLG STEMS FM4 SQRT p=	STFORMLG DEAD STEM SQRT p=	STFORMLG DBH AGE SQRT p=
Pinus contorta		0.393	−0.228		−0.126	
Picea mariana						−0.312
Picea engelmannii 'x' glauca		−0.309			−0.274	0.340
Abies lasiocarpa			n/d			
Larix laricina	n/d			n/d		
Populus tremuloides			n/d			0.253
Betula papyrifera			n/d			
Populus balsamifera			n/d	−0.473		
All–species		0.264		0.121		0.109

+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STEM–FORM and MICRO SITE–CONDITIONS
LOG base 10 STEM–FORM (STFORMLG)
MICRO SITE–CONDITIONS
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	STFORMLG MINERAL p=	STFORMLG WETLAND p=	STFORMLG WOOD p=	STFORMLG SOLUM THICKNESS p=	STFORMLG pH p=	STFORMLG TEXTURE p=	STFORMLG DRAINAGE p=
Pinus contorta	0.143	0.174	−0.164				
Picea mariana	n/d				0.292+		
Picea engelmannii 'x' glauca	n/d	0.271				−0.195+	
Abies lasiocarpa	n/d	n/d					
Larix laricina	n/d						
Populus tremuloides	n/d	n/d					
Betula papyrifera	n/d	n/d	−0.632+				
Populus balsamifera	n/d	n/d					
All–species	0.120		−0.142				

+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STEM–FORM and MICRO SITE–CONDITIONS continued
LOG base 10 STEM–FORM (STFORMLG)
MICRO SITE–CONDITIONS
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	STFORMLG REGOSOL p=	STFORMLG BRUNISOL p=	STFORMLG LUVISOL p=	STFORMLG GLEYSOL p=	STFORMLG ORGANIC p=
Pinus contorta					n/d
Picea mariana					
Picea engelmannii 'x' glauca					
Abies lasiocarpa	n/d				n/d
Larix laricina	n/d	n/d	n/d		
Populus tremuloides				0.239+	n/d
Betula papyrifera	n/d				n/d
Populus balsamifera					n/d
All–species					

+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STEM–FORM and PLANT ASSOCIATION
LOG base 10 STEM–FORM (STFORMLG)
PLANT ASSOCIATION
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	STFORMLG AW3 p=	STFORMLG AW4 p=	STFORMLG BW4 p=	STFORMLG PB4 p=	STFORMLG PLAW2 p=	STFORMLG PLAW4 p=	STFORMLG PLFA3 p=	STFORMLG PL4 p=
Pinus contorta		n/d	n/d	n/d			0.177	
Picea mariana	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
Picea engelmannii 'x' glauca			n/d				n/d	
Abies lasiocarpa	n/d	n/d	n/d	n/d	n/d			
Larix laricina	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
Populus tremuloides					0.334		n/d	n/d
Betula papyrifera	n/d				n/d	n/d	n/d	n/d
Populus balsamifera					n/d		n/d	n/d
All–species	0.132				0.234	0.142	0.145	

+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STEM–FORM and PLANT ASSOCIATION continued
LOG base 10 STEM–FORM (STFORMLG)
PLANT ASSOCIATION
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	STFORMLG PL2 p=	STFORMLG PLSB4 p=	STFORMLG SBPL6 p=	STFORMLG SB7 p=	STFORMLG SX5 p=	STFORMLG SXPL5 p=	STFORMLG M6 p=
Pinus contorta							
Picea mariana	0.317					n/d	
Picea engelmannii 'x' glauca	n/d			n/d	−0.230	−0.295	
Abies lasiocarpa	n/d	n/d		n/d			n/d
Larix laricina	n/d		n/d		n/d	n/d	n/d
Populus tremuloides	n/d		n/d	n/d			n/d
Betula papyrifera	n/d		n/d	n/d		n/d	n/d
Populus balsamifera	n/d	n/d	n/d	n/d		n/d	n/d
All–species	0.122						0.100

+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS

STEM–FORM, MACRO SITE–CONDITIONS plus STAND–CLOSURE

LOG base 10 STEM–FORM (STFORMLG)

TOTAL BASAL AREA (TBA)

LOG base 10 TOTAL NUMBER OF STEMS (TNSLOG)

MACRO SITE–CONDITIONS

PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	STFORMLG MONTANE p=	STFORMLG SUBALPINE p=	STFORMLG BOREAL UPLAND p=	STFORMLG BOREAL FOOTHILLS p=	STFORMLG BOREAL MIXEDWD p=	STFORMLG FLUVIAL p=	STFORMLG SOUTH EFFECT p=	STFORMLG WEST EFFECT p=	STFORMLG ELEVATION p=
Pinus contorta			−0.332						0.524
Picea mariana	n/d								0.462
Picea engelmannii 'x' glauca			0.233						0.453
Abies lasiocarpa	n/d				n/d				0.584
Larix laricina	n/d	n/d	n/d			n/d			
Populus tremuloides		n/d						−0.240+	
Betula papyrifera	n/d	n/d	n/d						
Populus balsamifera				0.591					
All–species				0.136	0.172	0.093			0.351

+ r is not significantly different from 0.000 (alpha=.05/2)

'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations

n/d no data

PARTIAL CORRELATION COEFFICIENTS
STEM–FORM, MESO SITE–CONDITIONS plus STAND–CLOSURE
LOG base 10 STEM–FORM (STFORMLG)
TOTAL BASAL AREA (TBA)
LOG base 10 TOTAL NUMBER OF STEMS (TNSLOG)
MESO SITE–CONDITIONS
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	STFORMLG STEMS FM1 SQRT p=	STFORMLG STEMS FM2 SQRT p=	STFORMLG STEMS FM3 SQRT p=	STFORMLG STEMS FM4 SQRT p=	STFORMLG DEAD STEMS SQRT p=	STFORMLG DBH AGE SQRT p=	STFORMLG TBA p=	STFORMLG TNSLOG p=
Pinus contorta		0.381	−0.199					−0.429
Picea mariana								−0.558
Picea engelmannii 'x' glauca								−0.340
Abies lasiocarpa			n/d					−0.467
Larix laricina	n/d			n/d				
Populus tremuloides	−0.410		n/d					−0.645
Betula papyrifera			n/d					
Populus balsamifera			n/d	−0.473+				
All–species		0.313						−0.448

\+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS

STEM–FORM, MICRO SITE–CONDITIONS plus STAND–CLOSURE

LOG base 10 STEM–FORM (STFORMLG)

TOTAL BASAL AREA (TBA)

LOG base 10 TOTAL NUMBER OF STEMS (TNSLOG)

MICRO SITE–CONDITIONS

PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	STFORMLG MINERAL p=	STFORMLG WETLAND p=	STFORMLG WOOD p=	STFORMLG SOLUM THICKNESS p=	STFORMLG pH p=	STFORMLG TEXTURE p=	STFORMLG DRAINAGE P=
Pinus contorta	0.222		−0.221				
Picea mariana	n/d						
Picea engelmannii 'x' glauca	n/d	0.303					
Abies lasiocarpa	n/d	n/d					
Larix laricina	n/d						
Populus tremuloides	n/d	n/d		0.254+			
Betula papyrifera	n/d	n/d	−0.632+				
Populus balsamifera	n/d	n/d					
All–species	0.148		−0.131		−0.119	−0.091	

\+ r is not significantly different from 0.000 (alpha=.05/2)

'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations

n/d no data for this species for this variable

empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS

STEM–FORM, MICRO SITE–CONDITIONS plus STAND–CLOSURE continued

LOG base 10 STEM–FORM (STFORMLG)

TOTAL BASAL AREA (TBA)

LOG base 10 TOTAL NUMBER OF STEMS (TNSLOG)

MICRO SITE–CONDITIONS

PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	STFORMLG REGOSOL p=	STFORMLG BRUNISOL p=	STFORMLG LUVISOL p=	STFORMLG GLEYSOL p=	STFORMLG ORGANIC p=
Pinus contorta					n/d
Picea mariana					
Picea engelmannii 'x' glauca					0.245
Abies lasiocarpa	n/d				n/d
Larix laricina	n/d	n/d	n/d		
Populus tremuloides				−0.381	n/d
Betula papyrifera	n/d				n/d
Populus balsamifera					n/d
All–species				0.095	

\+ r is not significantly different from 0.000 (alpha=.05/2)

'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations

n/d no data for this species for this variable

empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS

STEM–FORM and PLANT ASSOCIATION plus STAND–CLOSURE

LOG base 10 STEM–FORM (STFORMLG)

TOTAL BASAL AREA (TBA)

LOG base 10 TOTAL NUMBER OF STEMS (TNSLOG)

PLANT ASSOCIATION

PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	STFORMLG AW3 p=	STFORMLG AW4 p=	STFORMLG BW4 p=	STFORMLG PB4 p=	STFORMLG PLAW2 p=	STFORMLG PLAW4 p=	STFORMLG PLFA3 p=	STFORMLG PL4 p=
Pinus contorta		n/d	n/d	n/d				−0.172
Picea mariana	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
Picea engelmannii 'x' glauca			n/d	0.305		0.213	n/d	
Abies lasiocarpa	n/d	n/d	n/d	n/d	n/d			
Larix laricina	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
Populus tremuloides		−0.381	−0.501		0.333		n/d	n/d
Betula papyrifera	n/d				n/d	n/d	n/d	n/d
Populus balsamifera					n/d		n/d	n/d
All–species			−0.113	0.068+				

+ r is not significantly different from 0.000 (alpha=.05/2)

'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations

n/d no data for this species for this variable

empty cells – variables not part of regression

PARTIAL CORRELATION COEFFICIENTS
STEM–FORM and PLANT ASSOCIATION plus STAND–CLOSURE continued
LOG base 10 STEM–FORM (STFORMLG)
TOTAL BASAL AREA (TBA)
LOG base 10 TOTAL NUMBER OF STEMS (TNSLOG)
PLANT ASSOCIATION
PARTIAL CORRELATION COEFFICIENTS (p)

SPECIES	STFORMLG PL2 p=	STFORMLG PLSB4 p=	STFORMLG SBPL6 p=	STFORMLG SB7 p=	STFORMLG SX5 p=	STFORMLG SXPL5 p=	STFORMLG M6 p=
Pinus contorta						−0.247	
Picea mariana						n/d	
Picea engelmannii 'x' glauca	n/d			n/d			
Abies lasiocarpa	n/d	n/d		n/d			n/d
Larix laricina	n/d		n/d		n/d	n/d	n/d
Populus tremuloides	n/d		n/d	n/d			n/d
Betula papyrifera	n/d		n/d	n/d		n/d	n/d
Populus balsamifera	n/d	n/d	n/d	n/d		n/d	n/d
All–species					−0.110	−0.156	

\+ r is not significantly different from 0.000 (alpha=.05/2)
'x' Picea Hybrid is composed of the intergrade from Picea glauca at lower elevations to Picea engelmannii at higher elevations
n/d no data for this species for this variable
empty cells – variables not part of regression

APPENDIX C - Statistical Methods

C1- Data Distribution - Frequency Analysis (Skewness, Kurtosis Tests)
- Transformation

C2- Group Differences - Nonparametric (Kruskal-Wallis Test)
- Homogeneity of Variance (Bartlett's Test, Box's Test)
- Analysis of Variance (F test)

C3- Factor Analysis - Principal Components Analysis

C4- Measures of Association - Cross-tabulation (Chi-square Test)
- Correlation (Bivariate, t-test, Z-test, Multiple, Partial, Semi-partial)
- Regression (Stepwise, F Test, Partial F Test, Durban-Watson Statistic)

C1- Data Distribution

In order to utilize data in statistical analysis, normal distribution is required, particularly if the degrees of freedom are less than 20 (Tabachnick and Fidell, 1989). Data were tested for normality in distribution utilizing a frequency analysis. Unilateral transformations were performed where necessary.

Frequency Analysis: The data distributions for numeric (continuous) data were examined as histograms; the distributions for categorical data were examined as barcharts. The numeric data were tested for skewness and kurtosis. Non-normality in distribution may be present in other ways but the effect is less. Kurtosis is likely to have the most effect; the analysis of variance F test is most likely to be affected. Values for kurtosis that fall between ± 2.00 are less likely to have an effect where the sample size is large (n=20) (Lindman, 1992 pg 22).

Test for Skewness: Skewness is a reflection of the symmetry of the distribution. Positive skewness indicates an excess of observations to the left; negative skewness indicates an excess of observations to the right.

H_o: The skewness of the population distribution is not significantly different from normal (skew = 0.000)

H_a: The population distribution does not have a normal distribution (skew > 0.000 or skew < 0.000)

The test statistic was compared to the z distribution with alpha=0.050. H_o was rejected if the test statistic was greater than the z distribution value. The test statistic is as follows:

$$Z = \frac{S - 0}{s_s}$$

$$S = \text{skewness} = \frac{K_3}{(K_2)^{3/2}}$$

K_1, K_2, K_3, K_4 = Fisher's K statistics

N = total sample size

s_s = standard error of skewness $\sqrt{\frac{6}{N}}$

Test for Kurtosis: Kurtosis is a reflection of the peakedness of the distribution. Positive kurtosis indicates a very peaked distribution with too few observations in the tails; negative kurtosis indicates a very flat distribution with too many observations in the tails.

H_o: The kurtosis of the population distribution is not significantly different from normal (kurtosis = 0.000)

H_a: The population does not have a normal distribution (kurtosis > 0.000 or kurtosis < 0.000)

The test statistic was compared to the z distribution with alpha=0.050. H_o was rejected if the test statistic was greater than the z distribution value. The test statistic is as follows:

$$Z = \frac{K - 0}{s_k}$$

$$K = \text{kurtosis} = \frac{K_4}{(K_2)^2}$$

K_1, K_2, K_3, K_4 = Fisher's K statistics

N = total sample size

k_s = standard error of kurtosis $\sqrt{\frac{24}{N}}$

(Tabachnick and Fidell, 1989 pg 72-73; Kanji, 1993 pg 43)

Transformation: Logarithm base 10, square root and inverse transformations were performed to normalize the data

and provide a better fit in the regression analysis. Where values of 0 were included, a constant was added to bring the minimum value up to 1 before transformation.

Logarithmic base 10 Transformation: Logarithmic transformation was performed when the data distribution was very positively skewed and very peaked. The conversion is as follows:

$Y' = \log_{10} Y$

Square Root Transformation: Square root transformation was performed when the data distribution was moderately positively skewed and somewhat peaked. The conversion is as follows:

$Y' = Y^{1/2}$

Inverse Transformation: Inverse transformations were performed on an inverse J-shaped curve; the data were very positively skewed but dished. The conversion is as follows:

$Y' = 1/Y$

C2- Group Differences

The tests for group differences fall into two categories, non-parametric and parametric. In order to perform parametric tests, analysis of variance in this case, certain assumptions must be met. These are:

1.Random samples are selected from each of k populations or groups.

2.A value of a specified (dependent) variable is recorded for each experimental unit sample.

3.The dependent variable is normally distributed in each population.

4.The variance of the dependent variable is the same in each population.

(Kleinbaum and Kupper, 1978 pg 248)

Non-parametric: The assumptions in non-parametric tests are minimal; unequal variance is not a criterion. The median and Kruskal-Wallis tests are non-parametric procedures to test for differences between more than two independent samples. Kruskal-Wallis was used as it uses more information and is therefore more powerful.

Kruskal-Wallis: The Kruskal-Wallis test was used to test the hypothesis that all groups are samples from the same population. It is a one-way analysis of variance by ranks with the following assumptions:

1.The data for analysis consists of k random samples of sizes n_1, $n_2,\ldots,n_k$, where n_1, $n_2,\ldots,n_k$ are greater than or equal to 5.

2.The observations are independent both within and among samples.

3.The variable of interest is continuous.

4.The measurement scale is at least ordinal.

5.The populations are identical except for a possible difference in location for at least one population.

H_o: The k population distribution functions are identical

H_a: The k populations do not all have the same median

The individual observations for the total of all k samples are ranked from smallest to largest (1 to N). The mean rank for a sample population is the sum of the ranks within that sample divided by the number of observations. The test statistic was compared to a Chi-square distribution using alpha = 0.050. H_o was rejected if the test statistic was greater than the Chi-square value. The test statistic is as follows:

$$T = \frac{(n - 1)\ [S_t^2 - C]}{(S_r^2 - C)}$$

k = number of populations
n = total sample size
x_{ij} = x is the jth observation in the ith sample
n_i = size of sample
r_{ij} = rank allocated to observation x_{ij}
s_i = sum of the ranks in the ith sample
N = total observations = $\Sigma_i n_i$
S_t^2 = total sum of squares = $\Sigma_i (s_i^2/n_i)$
S_r^2 = rank sum of squares = $\Sigma_{ij} (r_{ij}^2)$
C = correction for the mean = $\frac{1}{4}N(N+1)^2$
df = degrees of freedom = k-1

(Daniel, 1978 pg 200; Sprent, 1990 pg 113)

Parametric: Tests for homogeneity of variance were performed in order to determine if an analysis of variance could be performed. Homogeneity of the sample variances was tested to determine if an analysis of variance could be performed. The analysis of variance procedure is composed of two parts. Initially tests were performed to determine whether any significant differences existed between the groups. If significant differences

existed, tests were performed to determine which groups were different.

Homogeneity of Variance: There are four tests available to check for unequal variances. These are Hartley's, Cochrane's, Bartlett's and Box's. Hartley's test is applicable where the number of groups is five or less; Cochrane's test is applicable where the observation numbers within the groups are equal; Bartlett's test is applicable where the sample sizes are unequal but is sensitive to departures from a normal distribution. Box's test is a more robust procedure which is applicable to data with more than five groups with unequal numbers of observations within each group. It should be noted that the results from an analysis of variance may be good despite unequal variances if the sample sizes are all equal or if the larger samples correspond to populations with larger variances (Milliken and Johnson, 1992 pg 17).

H_o: The k population distribution functions are identical

H_a: The k populations do not all have the same median

Bartlett's Test: Bartlett's test compares the logarithm of the mean of the sample variances with the mean of their logarithms. Differences in variance are masked if the kurtosis is smaller than 0.000 (a dished distribution). Non-existent differences are exhibited if the kurtosis is greater than 0.000 (a peaked distribution) (Lindman, 1992 pg 23). The test statistic for Bartlett's test is compared to the Chi-square distribution utilizing alpha = 0.050. The test statistic for Bartlett's test is as follows:

$$B = \frac{2.30259}{C}\left[\sum (n_j-1)\ \log s^2 - \sum (n_j-1)\ \log \sigma_j^2\right]$$

n_j = size of sample
σ_j = variance of sample n_j
k = number of populations

$$s = \text{overall variance} = \frac{\sum_{j=1}^{k} (n_j-1)\ \sigma_j^2}{\sum_{j=1}^{k} (n_j-1)}$$

$$C = 1 + \frac{1}{3\ (k-1)}\left[\sum \frac{1}{(n_j-1)} - \frac{1}{\sum (n_j-1)}\right]$$

df = degrees of freedom = k-1

(Kanji, 1993 pg 62)

Box's Test: Box's test is more robust with respect to deviations from a normal distribution but it is not very powerful for small data sets (King and Julstrom, 1982 pg 319; Milliken and Johnson, 1992 pg 23). With Box's test, data within each group are randomly partitioned into subgroups of approximately equal size. The logarithm (base 10) of the variance of each subgroup is calculated. A one-way analysis of variance is performed on the resulting data. The test statistic is compared to the F distribution utilizing alpha=0.050. H_o was rejected if the test statistic was greater than the F distribution. Subdivision of the data produces the following table:

	Group1	Group2	Group3	Group4
Subgroup1	$\log\sigma_{11}$	$\log\sigma_{12}$	$\log\sigma_{13}$	$\log\sigma_{14}$
Subgroup2	$\log\sigma_{21}$	$\log\sigma_{22}$	$\log\sigma_{23}$	$\log\sigma_{24}$
Subgroup3	$\log\sigma_{31}$	$\log\sigma_{32}$	$\log\sigma_{33}$	$\log\sigma_{34}$
Total	tot_1	tot_2	tot_3	tot_4

n = number of Groups + Subgroups

k = number of Groups

σ_{rc} = variance of $Subgroup_{row}$, $Group_{column}$

$df_{numerator}$ = k-1 degrees of freedom

$df_{denominator}$ = n-k degrees of freedom

(Milliken and Johnson, 1992 pg 18-22)

Analysis of Variance: Analysis of variance is used to determine the differences in means between samples of the variance. It is fairly robust to violations in the assumptions, which means that the procedure may be applied as long as the violations are not severe. Normality does not have to be exactly satisfied if the samples are large (more than 20 from each population); the consequences for large deviations are more severe for random factors than fixed factors. The assumption of equal variance can be mildly violated without ramifications if the sample sizes are roughly equal. Violation of the assumption of independence of the observations may lead to errors in inference for both fixed and random factors. This study deals with both random and fixed factors. Random factors have levels which are drawn from a

larger population of level; fixed factors have no other levels than those included in the analysis (Kleinbaum and Kupper, 1978 pg 247).

F Test: The F distribution is the ratio of two independent Chi-square distributions; it is defined by two independent values for degrees of freedom. The F test was used to determine if there were significant differences in the means between sample populations.

H_o: The k population means are all equal

H_a: The k populations means are not all equal

The test statistic is compared to the F distribution with alpha = 0.050. H_o is rejected if the test statistic is greater than the value for the F distribution at one minus alpha. The test statistic is as follows:

$$F = \frac{MST}{MSE}$$

$$MST = \left[\sum_{i=1}^{k} (T_i^2/n_i) - G^2/n \right] / (k-1)$$

$$MSE = \left[\sum_{i=1}^{k} \sum_{j=1}^{n_i} Y_{ij}^2 - \sum (T_i^2/n_i) \right] / (n-k)$$

Y_{ij} = each observation in the sample
T_i = total for each sample
G = grand total over all samples
$df_{numerator}$ = k-1 degrees of freedom
$df_{denominator}$ = n-k degrees of freedom

(Kleinbaum and Kupper, 1978 pg 249-251)

C3- Factor Analysis

Factor analysis was used as a screening tool; in multiple regression there may be problems associated with analyzing data where there is high correlation between the independent variables. A factor is said to exist when a group of variables display commonality. Principal components analysis, a form of factor analysis, was used to reduce the groups of inter-correlated **site-conditions** variables to factors.

Principal Components Analysis: Principal components analysis is an exploratory tool; there are no assumptions regarding the underlying relationships. The procedure was used to select a single variable from each component. A graphic representation of principal components analysis with an orthogonal rotation would produce multiple axes with the maximum distance between each pair of axes (90^0). Each pair of axes corresponds to the orientation of a single factor. Each factor explains a certain amount of the variance in the entire data set. An orthogonal rotation is based on no correlation between the factors; an oblique rotation, where the distance between the pairs of axes is not maximum, is based on some correlation between the factors. Each additional factor explains proportionally less of the variance as the amount of unexplained variance drops with an increase in the number of factors.

The result of a principal components analysis is a matrix of the loading values of each of the variables for each factor. Each loading corresponds to the correlation coefficient between the variable and the factor; high positive loadings indicate a high positive correlation and high negative loadings indicate a high

negative correlation. The eigenvalue, or latent root, is the sum of the squares of the loadings for each factor. Kaiser's criterion suggests that only those factors with an eigenvalue greater than 1.000 are considered to be common factors. The scree test involves a visual examination of the eigenvalues plotted against the factor number. The break point is assumed to be at the development of a linear relationship as the number of factors increases. The scree test is likely more effective when the number of factors is less than 20 (Childs, 1973 pg 42-44).

The values for the principal loadings for the macro, meso and micro variables are listed in the following table. The variables to be utilized in further analysis were selected from these loadings but do not always correspond to those with the highest values. As indicated in the text, preference was given to those variables with a normal distribution and also to variables which were not visual estimates. The selected variables were then utilized in further analysis.

Principal Components Analysis Results (Orthogonal Rotation)

Macro Variables

Factor	Eigenvalue	Cumulative %Variance	
1	2.833	56.7	Kaiser's Criterion
2	0.866	74.0	
3	0.691	87.8	
4	0.610	100.0	
5	0.000	100.0	Scree Test

Variable		Factor Loading	Variable Description
ELEV	*	not applicable	**Elevation**
SEFFECT	*		**South effect**
WEFFECT	*		**West effect**
NEFFECT	*		**North effect**
EEFFECT	*		**East effect**

Meso Variables

Factor	Eigenvalue	Cumulative %Variance	
1	3.262	32.6	
2	2.853	61.2	
3	2.044	81.6	
4	1.164	93.2	Kaiser's Criterion
5	0.599	99.2	
6	0.042	99.6	Scree Test
7	0.031	100.0	
8	0.005	100.0	
9	0.000	100.0	
10	0.000	100.0	

Variable		Factor Loading	Variable Description
LSFM1	*	1 (-.87)	**Live Stems Form1**
LSFM2	*	1 (.91)	**Live Stems Form2**
LSFM3	*	3 (.98)	**Live Stems Form3**
LSFM4	*	2 (-.97)	**Live Stems Form4**
TBFM1		1 (-.86)	**Total Basal Area Form1**
TBFM2		1 (.93)	**Total Basal Area Form2**
TBFM3		3 (.98)	**Total Basal Area Form3**

TBFM4		2 (-.96)	**Total Basal Area Form4**
DSM	*	4 (.84)	**Dead Stems**
DBHAGE	*	4 (.53)	**Tree Age**

Micro Variables

Factor	Eigenvalue	Cumulative %Variance	
1	3.567	19.8	
2	2.342	32.8	
3	1.918	43.5	
4	1.451	51.5	
5	1.274	58.6	
6	1.117	64.8	
7	1.063	70.7	Kaiser's Criterion
8	0.916	75.8	
9	0.747	80.0	
10	0.693	83.8	
11	0.605	87.2	
12	0.568	90.3	
13	0.520	93.2	Scree Test
14	0.400	95.5	
15	0.379	97.6	
16	0.269	99.1	
17	0.169	100.0	
18	0.001	100.0	

Variable	Factor Loading	Variable Description
TREE	7 (-.44)	**Tree Cover**
SHRUB	3 (-.55)	**Shrub Cover**

FORB		2 (-.64)	**Forb Cover**
GRAM		7 (.54)	**Graminoid Cover**
MOSS		2 (.83)	**Moss Cover**
LICHEN		6 (-.82)	**Lichen Cover**
WOOD	*	1 (.96)	**Dead Wood**
MINERAL	*	6 (-.83)	**Exposed Soil + Stones + Rock**
ORG		1 (-.97)	**Organic Material**
WATER	*	7 (.73)	**Open Water**
LFHTH		4 (.68)	**Organic Layer Thickness**
SOLUMTH	*	4 (-.88)	**Solum Thickness**
PH	*	3 (.72)	**Soil pH**
TEXTURE	*	5 (.76)	**Soil Texture**
CF		5 (-.64)	**Coarse Fragments**
DRAINAGE	*	2 (.62)	**Soil Drainage**
EMRNUM		2 (.65)	**Ecological Moisture Regime**
ENRNUM		3 (.79)	**Ecological Nutrient Regime**

* variables that were utilized in further analysis

C4- Measures of Association

The association between variables can be tested for categorical data utilizing cross-tabulation. In cross-tabulation, expected cell frequencies are compared to observed frequencies and a Chi-square test is used to determine if significant relationships occur. Numeric data can be tested utilizing correlation and regression. Correlation involves bivariate correlation coefficients between two variables and multiple correlation coefficients between one dependent variable and a number of independent variables. Multivariate analysis also generates partial and semi-partial correlation coefficients as well as the multiple correlation coefficient. Multiple correlation coefficients describe the overall relationship between the dependent variable and all of the independent variables; partial and semi-partial correlation coefficients describe the relationship between the dependent variable and each independent variable. In regression analysis, an equation or model is developed for the purpose of prediction; in multiple regression, one dependent variable is predicted by two or more independent variables.

Cross-tabulation: Cross-tabulations, also known as a contingency tables, are utilized to determine if a relationship exists between different levels of categorical variables. The expected frequencies are compared to the observed freqencies and evaluated for independence utilizing a Chi-square test. The following assumptions must be met for a Chi-square test:

1.The observations are a random sample from the population being analyzed.

2.Each individual observation may belong to only one category of each variable.

3.Minimum expected frequencies for any cell must be at least 1.00.

4.A maximum of 20% of the cells with an expected frequency less than 5.

H_o: The criteria of classification for the sampled populations are independent

H_a: The criteria of classification for the sampled populations are not independent

Chi-square Test: The Chi-square test of independence tests the hypothesis that the classification variables are independent for the population being examined. If the classifications are independent, the expected frequency should be based on the probability of one category multiplied by the probability of the other category. Chi-square is also used to test for homogeneity in populations; the expected frequencies are calculated on the basis of homogeneity in the population.

The test statistic for the Chi-square test is compared to the Chi-square distribution utilizing alpha=0.050. H_o was rejected if the test statistic was greater than the Chi-square distribution value. The test statistic is as follows:

$$X^2 = \sum_{i=1}^{r} \sum_{j=1}^{c} \left[\frac{(O_{ij} - E_{ij})^2}{E_{ij}} \right]$$

r = rows
c = columns
O_{ij} = observed frequency (count)
E_{ij} = expected frequency (count) $= n\left(\frac{n_i}{n}\right)\left(\frac{n_j}{n}\right)$
df = degrees of freedom = (r-1)(c-1)
(Daniel, 1978 pg 163)

Correlation: The correlation coefficient is a measure of the association between two or more variables. The square of the correlation coefficient is the coefficient of determination and is the measure of the strength of the relationship. The coefficient of correlation may be positive or negative. A positive correlation indicates that an increase in one variable produces an increase in the other; a negative correlation indicates that an increase in one variable produces a decrease in the other. If one variable does not produce a change in the other variable, then the two variables are uncorrelated. A lack of correlation indicates the lack of a linear relationship but does not exclude a non-linear relationship. Correlation may be bivariate, involving two variables, or multivariate, involving several variables. Multiple correlation may be total, partial or semi-partial depending on which aspects of the association are being assessed. The relationship between bivariate, multiple, partial and semi-partial correlation are depicted and described as follows:

Bivariate Correlation: The linear correlation between two variables is referred to as bivariate correlation. The bivariate correlation coefficient is calculated as follows:

$$r_{y|x} = \frac{\Sigma(x_i - \bar{x})(y^i - \bar{y})}{\left[\Sigma(x_i - \bar{x})^2 (y^i - \bar{y})^2\right]^{1/2}}$$

Two tests for significance for bivariate correlation were utilized. The correlation coefficient was tested for significant difference from 0.000. The correlation coefficient was also tested to determine if it was significantly less than 0.950.

H_o: The correlation coefficient of the population is not significantly different from 0.000

H_a: The correlation coefficient of the population is significantly different from 0.000

t-test: The t-test is used to determine whether the difference between the sample correlation coefficient and zero is statistically significant. It is based on the assumption of a linear relationship and that x and y originate from a bivariate normal distribution. This is a two-tailed test utilizing alpha = 0.050/2. The test statistic was compared to the t distribution. H_o was rejected if the absolute value of the test statistic was greater than the value of the t distribution. The test statistic is calculated as follows:

$$t = \frac{r}{\sqrt{(1-r^2)}} \sqrt{(n-2)}$$

r = correlation coefficient
n = number of observations

(Kanji, 1993 pg 33)

H_o: The correlation coefficient of the population is not significantly less than 0.950

H_a: The correlation coefficient of the population is significantly less than 0.950

Z-test: The Z-test is used to determine whether the difference between the sample correlation coefficient and a specified value is statistically significant. It is assumed that both x and y originate from normal distributions, that the variance in y is independent of x and that the relationship is linear. In this case, it is a one-tailed test utilizing alpha = 0.050. The test

statistic was compared to the Z distribution. H_o was rejected if the test statistic was greater than the value of the t distribution. The test statistic is calculated as follows:

$$z = \frac{Z - u_z}{\sigma_z}$$

$$Z = \tfrac{1}{2} \log_e \left[\frac{1+r}{1-r} \right]$$

$$u_z = \tfrac{1}{2} \log_e \left[\frac{1+p}{1-p} \right]$$

$$\sigma_z = \frac{1}{\sqrt{(n-3)}}$$

p = 0.950
r = correlation coefficient
n = number of observations

(one-tailed test) utilizing alpha = 0.050.

(Kanji, 1993 pg 34)

Multiple Correlation: When there are more than two variables involved, one of the variables may be designated as the dependent variable and the others as the independent variables. The measure of the association of all of the independent variables with the dependent variable. The multiple correlation coefficient is calculated as follows:

$$r_{y|x1,x2,\ldots,xk} = \frac{\sum_{i=1}^{n} (y_i - \bar{y})(Y^i - \bar{y})}{\left[\sum_{i=1}^{n} (y_i - \bar{y})^2 \sum_{i=1}^{n} (Y^i - \bar{y})^2 \right]^{1/2}}$$

y_i = observed value of y for any given value of x

$\bar{y}$ = mean of observed values of y

Y^i = predicted value of y for any given value of x

$$= \sum_{j=1}^{p} \beta_j x_{ij} + \beta_0$$

$\bar{y}$ = mean of predicted values of y
p = number of independent variables
β_j = parameters associated with the independent variables
x_{ij} = values for p independent variables for the ith case
β_0 = constant

The F test was utilized to establish whether the correlation coefficient was significantly different from 0.000.

H_o: The multiple correlation coefficient for the dependent variable is not significantly different from 0.000

H_a: The multiple correlation coefficient of the dependent variable is significantly different from 0.000

F test: The F test is used to determine whether the difference between the sample correlation coefficient and zero is statistically significant. The test statistic was compared to the F distribution utilizing alpha = 0.950. H_o was rejected if the test statistic was greater than the value of the F distribution at one minus alpha = 0.950. The test statistic is calculated as follows:

$$F = \frac{\frac{r^2}{1-r^2}}{\frac{n-k-1}{k}}$$

r = multiple correlation coefficient
n = number of observations
k = number of independent variables

(Kleinbaum and Kupper, 1978 pg 178)

Partial Correlation: Partial correlation coefficients describe the relationship between the dependent variable and an independent variable controlling for the relationship between the dependent variable and the other independent variables and also for the inter-relationship between the independent

variables. The partial correlation coefficient is calculated as follows:

$$p_{yx|z} = \frac{r_{yx} - r_{yz}\, r_{xz}}{\sqrt{[(1-r^2_{yz})\ (1-r^2_{xz})]}}$$

y = dependent variable
x = independent variable of interest
z = other independent variable
p = partial correlation coefficient

(Kleinbaum and Kupper, 1978 pg 167)

The partial correlation coefficients were tested for significant difference from 0.000 utilizing either a partial F test or a t-test.

H_o: The partial correlation coefficient for the independent variable, X, with the dependent variable is not significantly different from 0.000

H_a: The partial correlation coefficient for the independent variable, X, with the dependent variable is significantly different from 0.000

t-test: The t-test is used to determine whether the difference between the partial correlation coefficient and zero is statistically significant. This is a two-tailed test utilizing alpha = 0.050/2. The test statistic was compared to the t distribution. H_o was rejected if the absolute value of the test statistic was greater than the value of the t distribution at 1 - alpha/2. The test statistic is calculated as follows:

$$t = p_{yx|z1,z2,\ldots,zk}\ \sqrt{(n-k-2)}\ \sqrt{(1-p^2_{yx|z1,z2,\ldots,zk})}$$

y = dependent variable

x = independent variable of interest

z = other independent variable

p = partial correlation coefficient

n = number of observations

k = number of independent variables excluding X

df = degrees of freedom = n-k-2

(Kleinbaun and Kupper, 1978 pg 171)

Semi-partial Correlation: The semi-partial correlation coefficient describes the relationship between the dependent variable and an independent variable controlling for the inter-relationship between the independent variables only; it is a measure of the independent contribution of each individual independent variable to the relationship with the dependent variable. The semi-partial correlation coefficient is calculated as follows:

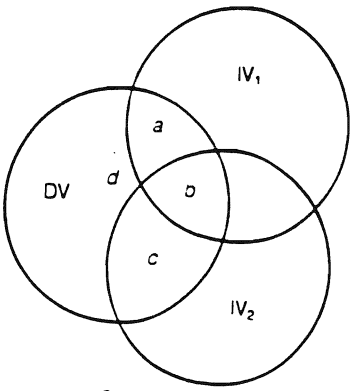
$$s_{yx|z} = \frac{r_{yx} - r_{yz}\, r_{xz}}{\sqrt{(1-r_{xz})^2}}$$

y = dependent variable
x = independent variable of interest
z = other independent variable
s = semi-partial correlation coefficient

The semi-partial correlation coefficients were not tested for significant difference from 0.000.

The relationship between bivariate, multiple, partial and semi-partial correlation is depicted below:

multiple correlation	r_i^2	$(a + b + c)/(a + b + c + d)$
bivariate correlation	r_i^2	IV_1 $(a + b)/(a + b + c + d)$ IV_2 $(c + b)/(a + b + c + d)$
semi-partial correlation	sr_i^2	IV_1 $a/(a + b + c + d)$ IV_2 $c/(a + b + c + d)$
partial correlation	pr_i^2	IV_1 $a/(a + d)$ IV_2 $c/(c + d)$



(Tabachnick and Fidell, 1989 pg 153; Stevens, 1986 pg 64)

It should be noted that the amount of variance accounted for by the independent variables is dependent upon their order of entry (Tabachnick and Fidell, 1989 pg 156; Stevens, 1986 pg 64-65).

Regression: Regression equations are developed in order to predict one variable, the dependent variable, with another variable, the independent variable. The dependent variable is so named as it is assumed to be dependent on the values of the independent variable. If there is a direct relationship, the regression is linear; if the independent variable must be mathematically transformed, the regression is non-linear. Regression equations may be used to describe the relationship between the independent variable and the dependent variable in terms of the slope and intercept. Linear regression takes the following general form:

$y = \beta_1 x + \beta_0 + \epsilon$

y = dependent variable

x = independent variable

β_1 = slope

β_0 = constant

ϵ = error

Multiple Regression: Multiple regression involves the prediction of a single dependent variable by two or more independent variables. Linear multiple regression has the following generalized form:

$$y_i = \sum_{j=1}^{k} \beta_j x_{ij} + \beta_0 + \epsilon_i$$

y_i = observed value for dependent variable
k = number of independent variables
β_j = parameters associated with the independent variables

x_{ij} = values for p independent variables for the ith case
$ß_0$ = constant
ϵ_i = error

In order to perform a linear multiple regression analysis certain assumptions have to be met to achieve conclusive results. These assumption are as follows:

1.For any combination of the independent variables x_1, x_2,..., x_k the dependent variable y is a random variable with a certain probability distribution.

2.The values for y are statistically independent.

3.The mean value of y is a linear function of each combination of x_1, x_2,..., x_k.

4.The variance of y is the same for any fixed combination of x_1, x_2,...,x_k. This is the assumption of homoscedasticity.

5.For any value of x_1, x_2,...,x_k, y has a normal distribution. Tests for significance are fairly robust; this assumption can be mildly violated without a loss of reliability.

(Kleinbaum and Kupper, 1978 pg 136-137)

There are several techniques to developing a multiple regression model; these include all-possible, backward-elimination, forward-selection and stepwise regressions. In all-possible regressions, every possible regression equation, including every combination of independent variables, is tested for the best fit. In backward-elimination, all of the independent variables are initially included in the analysis and variables that do not contribute significantly to the analysis are subsequently eliminated. In forward-selection, each independent variable, beginning with the variable most highly correlated with the dependent variable, enters the analysis and the equation is tested for

improvement. Stepwise regression follows the forward-selection procedure but re-evaluates the equation after each step to determine if any variables can be eliminated.

Stepwise Regression: Stepwise regression analysis is performed in the following manner:

1) the independent variable with the highest significant correlation with the independent variable is entered into the regression equation first.

2) the partial F statistic for each remaining independent variable is calculated as if that variable were included in the regression equation.

3) the variable with the highest partial F statistic is selected for the regression equation.

4) the partial F statistic for each variable within the regression equation is calculated and tested for significance; if significant it is included.

5) the partial F statistics are also examined to determine if any of the independent variables can be removed from the equation; addition of a new variable may reduce the contribution of one or more of the previously included variables.

(Kleinbaum and Kupper, 1978 pg 227-232)

The F test was utilized to establish whether the overall regression was significant.

F test: The F distribution is the ratio of two independent Chi-square distributions; it is defined by two independent values for degrees of freedom. The F test was used to determine if the independent variables x_1, x_2, ..., x_k help to predict the dependent variable y.

H_o: The independent variables x_1, x_2,..., x_k do not help to predict the dependent variable y

H_a: The independent variables x_1, x_2,..., x_k help to predict the dependent variable y

The test statistic is compared to the F distribution with alpha = 0.050. H_o is rejected if the test statistic is greater than the value for the F distribution at one minus alpha = 0.950. The test statistic, which is statistically equivalent to the test statistic for multiple correlation, is as follows:

$$F = \frac{MSR}{MSE}$$

$$MSR = \text{mean square regression} = \frac{1}{k} \sum_{i=1}^{n} (Y_i - \bar{y})^2$$

$$MSE = \text{mean square residual} = \frac{1}{n-k-1} \sum_{i=1}^{n} (y_i - Y_i)^2$$

n = number of observations
k = number of independent variables in the equation
y_i = each observation in the sample
Y_i = predicted value for the dependent variable
$\bar{y}$ = sample mean
$df_{numerator}$ = k degrees of freedom
$df_{denominator}$ = n-k-1 degrees of freedom

(Kleinbaum and Kupper, 1978 pg 140)

Partial F Test: The partial F test was used to determine the contribution of each of the independent variables x_1, x_2,..., x_k in predicting the dependent variable y.

H_o: The independent variable x does not help to predict the dependent variable y given that z1, z2,..., zk are already in the equation

H_a: The independent variable x does help to predict the dependent variable y given that z1, z2,..., zk are already in the equation

The test statistic is compared to the F distribution with alpha = 0.050. H_o is rejected if the test statistic is greater than the value for the F distribution at one minus alpha = 0.950. The test statistic is as follows:

$$F = \frac{SSR(x, z1, z2, \ldots, zk) - SSR(z1, z2, \ldots, zk)}{MSE(x, z1, z2, \ldots, zk)}$$

$$SSR = \text{sum squares regression} = \sum_{i=1}^{n} (Y_i - \bar{y})^2$$

$$MSE = \text{mean square residual} = \frac{1}{n-k-1} \sum_{i=1}^{n} (y_i - Y_i)^2$$

n = number of observations
k = number of independent variables in the equation
y_i = each observation in the sample
Y_i = predicted value for the dependent variable
$\bar{y}$ = sample mean
$df_{numerator}$ = k degrees of freedom
$df_{denominator}$ = n-k-1 degrees of freedom

(Kleinbaum and Kupper, 1978 pg 84, 140, 178)

Durban-Watson Statistic: The Durbin-Watson statistic was used to test for autocorrelation in the error terms in the regression model. Autocorrelation occurs when the error terms are correlated and the graphical analysis of the standardized residuals against cumulative frequency reveals departures from normality in distribution. Non-normality in distribution may exist for a number of reasons:

1.An inappropriate regression model has been chosen.

2.The variances of the independent variables are not homogeneous.

3.The number of residuals is too small to provide sufficient information.

(Kleinbaum and Kupper, 1978 pg 239)

The presence of autocorrelation creates problems in analysis and valuable information will be missing from the model. The procedure only tests for positive autocorrelation; negative autocorrelation is uncommon. The test is based on a first order autoregression model:

$\epsilon_i = p_a\epsilon_{i-1} + \delta_i$, δ_i are independently and identically distributed as N $(0, \sigma_{y|x})$

H_o: The error terms are not positively autocorrelated ($p_a = 0.000$)

H_a: The error terms are positively autocorrelated ($p_a > 0.000$)

The test statistic was compared to a table of upper and lower critical values for the Durbin-Watson statistic using alpha=0.050*. H_o was rejected if $d < d_l$. H_o was accepted rejected if $d > d_u$. If $d_l \leq d \leq d_u$ the test was inconclusive. The test statistic is as follows:

$$d = \frac{\Sigma\ (\epsilon_i - \epsilon_{i-1})^2}{\Sigma\ \epsilon_i^2}$$

* The table of critical values did not include values for more than five independent variables or where n was less than 15 or greater than 100. Visual extrapolation was utilized to determine if significant difference was present.

(Berenson *et al.*, 1983 pg 406-410)

APPENDIX D - Data

D1- Diskette

Fortran Programs - 1SOURCE.SIT

SPSSx Programs - 2SPSSX.ENV/VEG/SOI/MEN/SIT

- 3SPSSX.LOC
- 3SPSSX.PL/SB/SX/FA/LT/AW/BW/PB/ALL
- 4SPSSX.PL/SB/SX/FA/LT/AW/BW/PB/ALL
- 5SPSSX.ANV
- 5SPSSX.PL/SB/SX/FA/LT/AW/BW/PB/ALL
- 6GSPSSX.PCA
- 6GSPSSX.PL/SB/SX/FA/LT/AW/BW/PB/ALL
- 6NSPSSX.PCA
- 6NSPSSX.PL/SB/SX/FA/LT/AW/BW/PB/ALL
- 6LSPSSX.PCA
- 6LSPSSX.PL/SB/SX/FA/LT/AW/BW/PB/ALL
- 6CSPSSX.CRT
- 6CSPSSX.PL/SB/SX/FA/LT/AW/BW/PB/ALL
- 6SPSSX.COR
- 6SPSSX.PL/SB/SX/FA/LT/AW/BW/PB/ALL
- 6RSPSSX.PL/SB/SX/FA/LT/AW/BW/PB/ALL
- 7SPSSX.COR
- 7SPSSX.PL/SB/SX/FA/LT/AW/BW/PB/ALL
- 7RSPSSX.PL/SB/SX/FA/LT/AW/BW/PB/ALL
- 7BSPSSX.PL/SB/SX/FA/LT/AW/BW/PB/ALL

D2- Tape

Fortran Programs

SPSSx Programs

Raw Data - Environment

Vegetation

Soils

Timber Data

D1- Diskette

All programs are available as text files created on IBM-PC compatible diskettes (DOS 4.01). These programs were designed to run on a UNIX-based system; modification would be required for any other system.

Fortran Programs

Timber data compilation (Figure 7, Step 1)

1SOURCE.SIT - **stand-closure** calculation

- species volume sampling region coefficients, Alberta Provincial Standards

SPSSx Programs

System file generation from raw data

2SPSSX.ENV - system file for environmental data

2SPSSX.VEG - system file for vegetation data

2SPSSX.SOI - system file for soils data (not used in analysis)

2SPSSX.MEN - system file for raw mensuration data

2SPSSX.SIT - system file for compiled timber data

Species separation (Figure 7, Step 2)

3SPSSX.LOC- species geographic distributions all-species

3SPSSX.PL - system file *Pinus contorta*

3SPSSX.SB - system file *Picea mariana*

3SPSSX.SX - system file *Picea engelmannii x glauca*

3SPSSX.FA - system file *Abies lasiocarpa*

3SPSSX.LT - system file *Larix laricina*

3SPSSX.AW - system file *Populus tremuloides*

3SPSSX.BW - system file *Betula papyrifera*

3SPSSX.PB - system file *Populus balsamifera*

3SPSSX.ALL- system file all-species

Stand-closure variables elimination (Figure 7, Step 4)

4SPSSX.PL - distributions/correlations *Pinus contorta*

4SPSSX.SB - distributions/correlations *Picea mariana*

4SPSSX.SX - distributions/correlations *Picea engelmannii x glauca*

4SPSSX.FA - distributions/correlations *Abies lasiocarpa*

4SPSSX.LT - distributions/correlations *Larix laricina*

4SPSSX.AW - distributions/correlations *Populus tremuloides*

4SPSSX.BW - distributions/correlations *Betula papyrifera*

4SPSSX.PB - distributions/correlations *Populus tremuloides*

4SPSSX.ALL- distributions/correlations all-species

Stem-form calculation (Figure 7, Step 3)

Stem-form/stand-closure relationship (Figure 7, Step 5)

5SPSSX.ANV- analysis of variance **stem-form** by species all-species

5SPSSX.PL - distributions/correlations *Pinus contorta*

5SPSSX.SB - distributions/correlations *Picea mariana*

5SPSSX.SX - distributions/correlations *Picea engelmannii x glauca*

5SPSSX.FA - distributions/correlations *Abies lasiocarpa*

5SPSSX.LT - distributions/correlations *Larix laricina*

5SPSSX.AW - distributions/correlations *Populus tremuloides*

5SPSSX.BW - distributions/correlations *Betula papyrifera*

5SPSSX.PB - distributions/correlations *Populus balsamifera*

5SPSSX.ALL- distributions/correlations all-species

Stand-closure/site-conditions relationship (Figure 7, Step 6)

Macro variables (Figure 7, Step 6a)

6NSPSSX.PCA- principal components analysis all-species

6GSPSSX.PL - distributions *Pinus contorta*

6GSPSSX.SB - distributions *Picea mariana*

6GSPSSX.SX - distributions *Picea engelmannii x glauca*

6GSPSSX.FA - distributions *Abies lasiocarpa*

6GSPSSX.LT - distributions *Larix laricina*

6GSPSSX.AW - distributions *Populus tremuloides*

6GSPSSX.BW - distributions *Betula papyrifera*

6GSPSSX.PB - distributions *Populus balsamifera*

6GSPSSX.ALL- distributions all-species

Meso variables (Figure 7, Step 6b)

6NSPSSX.PCA- principal components analysis all-species

6NSPSSX.PL - distributions *Pinus contorta*

6NSPSSX.SB - distributions *Picea mariana*

6NSPSSX.SX - distributions *Picea engelmannii x glauca*

6NSPSSX.FA - distributions *Abies lasiocarpa*

6NSPSSX.LT - distributions *Larix laricina*

6NSPSSX.AW - distributions *Populus tremuloides*

6NSPSSX.BW - distributions *Betula papyrifera*

6NSPSSX.PB - distributions *Populus balsamifera*

6NSPSSX.ALL- distributions all-species

Micro variables (Figure 7, Step 6c)

6LSPSSX.PCA- principal components analysis all-species

6LSPSSX.PL - distributions *Pinus contorta*

6LSPSSX.SB - distributions *Picea mariana*

6LSPSSX.SX - distributions *Picea engelmannii x glauca*

6LSPSSX.FA - distributions *Abies lasiocarpa*

6LSPSSX.LT - distributions *Larix laricina*

6LSPSSX.AW - distributions *Populus tremuloides*

6LSPSSX.BW - distributions *Betula papyrifera*

6LSPSSX.PB - distributions *Populus balsamifera*

6LSPSSX.ALL- distributions all-species

Categorical variables (Figure 7, Step 6d)

6CSPSSX.CRT- cross-tabulations all-species

6CSPSSX.PL - distributions *Pinus contorta*

6CSPSSX.SB - distributions *Picea mariana*

6CSPSSX.SX - distributions *Picea engelmannii x glauca*

6CSPSSX.FA - distributions *Abies lasiocarpa*

6CSPSSX.LT - distributions *Larix laricina*

6CSPSSX.AW - distributions *Populus tremuloides*

6CSPSSX.BW - distributions *Betula papyrifera*

6CSPSSX.PB - distributions *Populus balsamifera*

6CSPSSX.ALL- distributions all-species

Stand-closure/site-conditions relationship (Figure 7, Step 6e)

Transformed vs untransformed **site-conditions**

6SPSSX.COR- correlations all-species

6SPSSX.PL - partial regression *Pinus contorta*

6SPSSX.SB - partial regression *Picea mariana*

6SPSSX.SX - partial regression *Picea engelmannii x glauca*

6SPSSX.FA - partial regression *Abies lasiocarpa*

6SPSSX.LT - partial regression *Larix laricina*

6SPSSX.AW - partial regression *Populus tremuloides*

6SPSSX.BW - partial regression *Betula papyrifera*

6SPSSX.PB - partial regression *Populus balsamifera*

6SPSSX.ALL- partial regression all-species

Final **site-conditions**

6RSPSSX.PL - full regression *Pinus contorta*

6RSPSSX.SB - full regression *Picea mariana*

6RSPSSX.SX - full regression *Picea engelmannii x glauca*

6RSPSSX.FA - full regression *Abies lasiocarpa*

6RSPSSX.LT - full regression *Larix laricina*

6RSPSSX.AW - full regression *Populus tremuloides*

6RSPSSX.BW - full regression *Betula papyrifera*

6RSPSSX.PB - full regression *Populus balsamifera*

6RSPSSX.ALL- full regression all-species

Stem-form/site-conditions relationship (Figure 7, Step 7)

Transformed vs untransformed **site-conditions**

7SPSSX.COR- correlations all-species

7SPSSX.PL - partial regression *Pinus contorta*

7SPSSX.SB - partial regression *Picea mariana*

7SPSSX.SX - partial regression *Picea engelmannii x glauca*

7SPSSX.FA - partial regression *Abies lasiocarpa*

7SPSSX.LT - partial regression *Larix laricina*

7SPSSX.AW - partial regression *Populus tremuloides*

7SPSSX.BW - partial regression *Betula papyrifera*

7SPSSX.PB - partial regression *Populus balsamifera*

7SPSSX.ALL- partial regression all-species

Final **site-conditions**

7RSPSSX.PL - full regression *Pinus contorta*

7RSPSSX.SB - full regression *Picea mariana*

7RSPSSX.SX - full regression *Picea engelmannii x glauca*

7RSPSSX.FA - full regression *Abies lasiocarpa*

7RSPSSX.LT - full regression *Larix laricina*

7RSPSSX.AW - full regression *Populus tremuloides*

7RSPSSX.BW - full regression *Betula papyrifera*

7RSPSSX.PB - full regression *Populus balsamifera*

7RSPSSX.ALL- full regression all-species

Stem-form/stand-closure/site-conditions relationship (Figure 7, Step 8)

7BSPSSX.PL - regression *Pinus contorta*

7BSPSSX.SB - regression *Picea mariana*

7BSPSSX.SX - regression *Picea engelmannii x glauca*

7BSPSSX.FA - regression *Abies lasiocarpa*

7BSPSSX.LT - regression *Larix laricina*

7BSPSSX.AW - regression *Populus tremuloides*

7BSPSSX.BW - regression *Betula papyrifera*

7BSPSSX.PB - regression *Populus balsamifera*

7BSPSSX.ALL- regression all-species

References for Programs

Berensen *et al.* 1983 -autocorrelation

Childs,D. 1973 -PCA

Daniel,W.W 1978 -nonparametric, cross-tabulation

Kanji,G.K. 1993 -skewness & kurtosis, homogeneity of variance, correlation

Kleinbaum,D.G. and Kupper,L.L. 1978 -regression, ANOVA, correlation, autocorrelation

Lindman,H.R. 1992 -frequency analysis, ANOVA

Loehlin,J.C. 1987 -PCA

Malik,H.J. and Mullen,K. 1973

Milliken,G.A. and Johnson,D.E. 1992 -homogeneity of variance

Sprent,P. 1990 -nonparametric

SPSS Inc. 1988 -programming language

Stevens,J. 1986 -correlation

Tabachnick,B.G. and Fidell,L.S. 1989 -skewness & kurtosis, correlation

Takeuchi,K. *et al*. 1982 -correlation, regression

Diskettes of the programs in the form of text files are available on request. Please contact:

Dr.J.Middleton

c/o Environmental Policy Institute

Brock University

St.Catharines, ON

L2S 3A1

(905-688-5550 Ext.3128)

D2- Tape

Environment

Vegetation

Soils

Timber Data

A tape of the raw data in the form of text files and SPSSx system files is available on request. Please contact:

Dr.J.Middleton

c/o Environmental Policy Institute

Brock University

St.Catharines, ON

L2S 3A1

(905-688-5550 Ext.3128)